Dynamic characterization of wind farms and their impact in power systems oscillations

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Abstract: *This paper has two main objectives: to explain the dynamic characterization of wind farms as part of their integration in power systems using modal analysis and to present a qualitative development for understanding the main factors that impact on the damping of the oscillation modes by incorporating wind farms based on variable speed wind turbines. Moreover, such developments are validated by performing simulations on a 2017 peak scenario for the Uruguayan electrical system, showing a strong interaction between the hydroelectrics power plants located on the Río Negro and future wind farms Palmatir and Agua Leguas.*

Keywords: *small-signal stability, angle stability, modal analysis, variable speed wind turbines, eigenvalues, eigenvectors, power system oscillations.*

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.
CN: Negative load.
D: Damping constant.
DFIG: Doubly-fed induction generator.
FC: Full-load converter.
M: Inertia constant.
U: Line-to-line voltage magnitude in the interconnection node (Terra and Baygorria).
U_∞: Line-to-line voltage magnitude in the infinite bus.
E_t: Line-to-earth voltage magnitude phase to earth in the interconnection node (Terra).
V_∞: Line-to-earth 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.

II. INTRODUCTION

Electromechanical oscillations in power systems are the result of the parallel operation of synchronous machines. There exist different patterns of exchange of kinetic energy manifested through the oscillation of electric power flows in transmission lines that interconnect the machines. These oscillation patterns are strongly dependent on the characteristics of the synchronous machines, the network topology under study and the power flow for a particular scenario. To ensure reliable operation of power systems, modes of oscillation must present an acceptable damping, so that those oscillations die out quickly when small perturbations affect the power system. Also, it is necessary to ensure that there are no modes with negative damping, which would cause unstable oscillations that would involve the trip of the machines concerned by the protection system in order to maintain stable operation of the power system.

The classic definition of angle stability in power systems is conceived as the ability of the system to maintain synchronism when the system is subjected to a disturbance. This definition it has to be adapted because of the incorporation of variable speed wind turbines. The variable speed wind turbines have the particularity of decoupling the rotation speed of the electric generators respect the frequency of the electrical network to which they are interconnected, through the inclusion of electronic converters that maximize power extraction process. This implies that the wind turbines will behave much as static sources of production of active and reactive power. Unlike synchronous generators, wind turbines are not linked to the grid through an internal angle, and therefore, no kinetic energy is exchanged with synchronous generators that originally forms part of the power systems.

Due to the asynchronous nature of the interconnection of these new machines, power systems will suffer changes in oscillatory dynamics, due mainly to the following reasons: changes in the architecture of transmission system to incorporate wind farms; replacement of part of the expansion of synchronous generators by wind farms; alteration in the dispatch of synchronous generators in order to incorporate the strongly

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varying wind power which depends on weather conditions; and the reduction of the power system inertia due to the injection of large amounts of power from wind turbines. All these distortions will result in an alteration of the synchronizing and damping torques of synchronous generators that may be beneficial or detrimental to the damping of the oscillatory modes depending on the particular operating conditions, and the relative location between conventional plants, demand centers and wind farms.

Because of this complex relationship that determines the operating conditions, it is very difficult to agree general statements on the consequences of the large scale inclusion of variable speed wind generation on power system dynamic behavior. This reaches the small signal stability and the transient behavior.

III. OBJECTIVES

The first aim of this paper is to analyze how the small signal stability of power systems will be affected with the inclusion of wind farms based on DFIG and FC technologies without changing the power dispatch of the synchronous generators in a hypotetical scenario of the Uruguayan power grid. The results of modal analysis are compared with a simplified model which assumes that wind farms act as a constant negative load.

The second objective is to show that the main effect that determines the evolution of oscillatory modes of the power grid due to the inclusion of wind power generation lies in the alteration of the operating points of the involved synchronous generators and the nature of the oscillatory modes affected. The analysis is conducted by simulating a real scenario where wind farms Palmatir/Agua Leguas and the hydroelectric plant Terra conform an area, and hydroelectric power plant Baygorria conforms another.

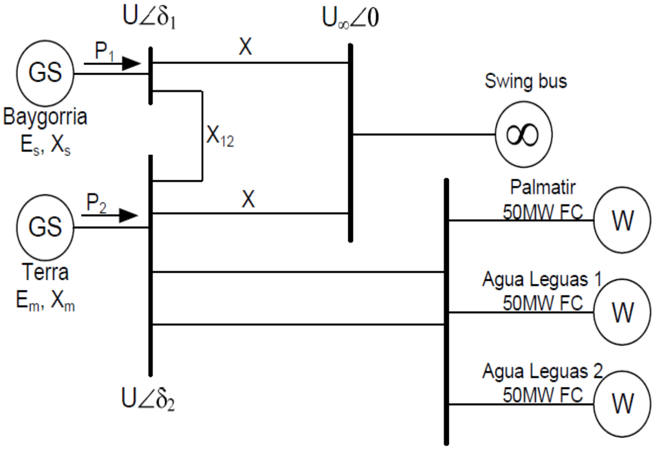

Figure 1: Simplified on-line diagram of the subsystem analyzed

Figure 1 shows a simplified model of the subsystem used for the analysis. Both areas are interconnected to the rest of the electrical grid (modelled as an infinite bus) through their own ties (X), and are interconnected through a weak line (X_{12}).

There are two oscillatory modes involved: RN (or common mode) in which both power plants oscillate in phase against the rest of the system and BY-T (or interarea mode) in which Terra oscillates against Baygorria. These modes of the uruguayan network were originally analized in [1]. The denomination of each mode for the present work is made in accordance with the mentioned reference.

Additionally, knowing the causes that determine the evolution of the damping of the oscillation modes due to the incorporation of wind power, it is analyzed and simulated the effect of reactive power redispatch of wind farms in order to clearly induce favorable changes on synchronizing and damping torques on the oscillatory modes related to Baygorria and Terra. This redispatch will improve substantially the performance of small signal response and the oscillatory behaviour when large disturbances ocurr, such as three phase shortcircuits in the vicinity of the hydroelectric power plants.

IV. DYNAMIC CHARACTERIZATION OF WIND FARMS

A. Modal analysis

Table 1 shows the evolution of the dominant oscillatory modes of the Uruguayan power system with and without the inclusion of wind energy considering the three models of wind turbines: FC, DFIG, CN.

MODO	Frecuencia (Hz)				Amortiguamiento (ζ)			
	BASE	CN	DFIG	FC	BASE	CN	DFIG	FC
UPM	1.45	1.45	1.45	1.45	4.15	4.13	4.12	4.12
PTI 1	3.08	3.06	3.05	3.05	6.58	6.44	6.43	6.43
PTI 2	3.23	3.20	3.20	3.20	6.74	6.59	6.58	6.58
TERRA 1	1.40	1.37	1.37	1.37	7.29	7.42	7.43	7.43
TERRA 2	1.40	1.37	1.37	1.37	7.29	7.42	7.43	7.43
TERRA 3	1.40	1.37	1.37	1.37	7.29	7.42	7.43	7.43
RN	1.20	1.19	1.19	1.19	8.01	7.64	7.48	7.48
IMPSA	x	x	1.94	x	x	x	7.78	x
PALMATIR	x	x	1.94	x	x	x	7.79	x
FINGANO	x	x	1.94	x	x	x	7.80	x
BY-T	1.30	1.29	1.29	1.29	8.69	9.18	9.23	9.25
PTI 3	1.30	1.29	1.29	1.29	9.32	9.17	9.17	9.17
PALMAR	1.51	1.48	1.48	1.48	8.43	9.51	9.52	9.53

Table 1: Modal analysis

The oscillatory behaviour is almost identical regardless of the wind farm model, which is an indication that wind farms effectively decouple the rotational speed of the machines from grid frequency and behave essentially like static power sources. In this analysis, the wind farms are not exchanging reactive power with the grid.

To be more decisive in this conclusion it is examined the participation factors (tables 2 and 3) and mode shapes for RN and BY-T oscillatory modes (figures 2 and 3), that are almost identical for the three models of wind farm examinated. In particular, small variations that exist in the damping calculated for the NL model compared to models of DFIG and FC modes are observed for RN and BY-T modes. Since the power flow scenario is identical in all cases, the reason atributted to the differences showed lies in the different control loops in the FC and DFIG models and the nonexistence of such a loop in the

NL model. Additionally, it is observed the occurrence of torsional modes in the case of DFIG wind turbine generators which do not interfere with the electromechanical oscillation modes.

From these studies, it is concluded that wind farms behave as static sources of active power or negative loads, and the impact of control loops on electromechanical modes are negligible. Furthermore, variations of the oscillation modes are mainly influenced by the setting of new operating points of synchronous generators due to redistribution of the power flow through the system.

VARIABLE	ESCENARIO			
	BASE	CN	DFIG	FC
98551 : BAYG ω_1	1	1	1	1
98552 : BAYG ω_2	1	1	1	1
98553 : BAYG ω_3	0.78	0.80	0.80	0.80
98177 : PTIG ω_7	0.63	0.90	0.90	0.86
98178 : PTIG ω_8	0.63	0.90	0.90	0.86
98541 : TERRA ω_1	0.43	0.64	0.67	0.68
98542 : TERRA ω_2	0.43	0.64	0.67	0.68
98543 : TERRA ω_3	0.43	0.64	0.67	0.68
98544 : TERRA ω_4	0.43	0.64	0.67	0.68
Amortiguamiento (%)	**8.01**	**7.64**	**7.48**	**7.48**
Frecuencia (Hz)	**1.20**	**1.19**	**1.19**	**1.19**

Table 2: RN oscillatory mode: participation factors

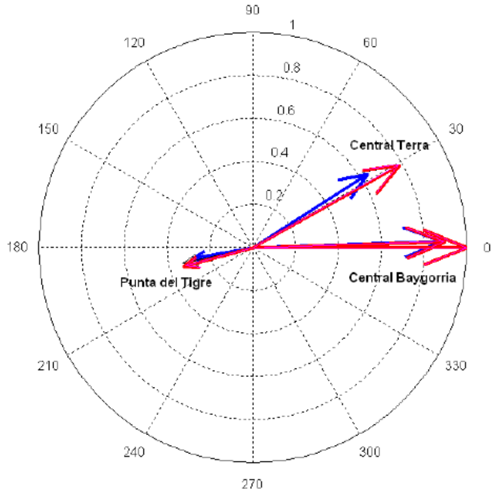

Figure 2: RN mode shape: base scenario (blue); NL, DFIG, FC scenarios (red)

VARIABLE	ESCENARIO			
	BASE	CN	DFIG	FC
98551 : BAYG ω_1	1	1	1	1
98552 : BAYG ω_2	1	1	1	1
98553 : BAYG ω_3	0.69	0.58	0.57	0.57
98541 : TERRA ω_1	0.82	0.57	0.55	0.54
98542 : TERRA ω_2	0.82	0.57	0.55	0.54
98543 : TERRA ω_3	0.82	0.57	0.55	0.54
98544 : TERRA ω_4	0.82	0.57	0.55	0.54
Amortiguamiento (%)	**8.69**	**9.18**	**9.23**	**9.25**
Frecuencia (Hz)	**1.30**	**1.29**	**1.29**	**1.29**

Table 3: BY-T oscillatory mode: participation factors

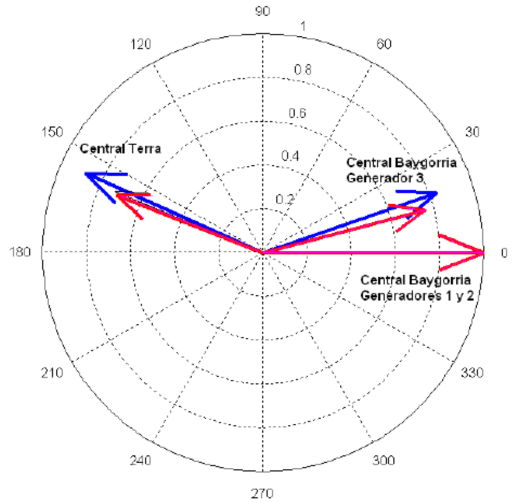

Figure 3: BY-T mode shape: base scenario (blue); NL, DFIG, FC scenarios (red)

B. *Reactive power exchange*

In case that wind farms inject or absorb reactive power from the grid, it can be reached the same conclusions: the main factor influencing the damping and frequency of the oscillation modes is due to the new operation points of synchronous generators. Further details on the analysis are provided in [2].

The differences in damping and synchronizing torques observed when wind farms inject or absorb reactive power will be analyzed for the particular case of the inclusion of wind farms Palmatir/Agua Leguas that will affect Terra-Baygorria.

C. *Increased power injected by wind farms*

This section examines the increasing power injection of Palmatir wind farm on the behaviour of RN mode and BY-T oscillatory modes. For this purpose, the power dispatched by the wind farm varies from 50MW to 150MW and the power factor varies between 0.95 inductive, 1 and 0.95 capacitive.

From Figures 4 and 5 it can be concluded that increasing active power injection from the wind farm, the RN mode damping tends to decrease, and BY-T mode damping tends to increase. Moreover, the reactive power consumption by the wind farm tends to improve the damping of RN mode for a given active power injection, while the damping BY-T mode is decremented. The opposite is also true. Injection of reactive power from the wind farm decreases the damping buffer RN and increases the damping of BY-T.

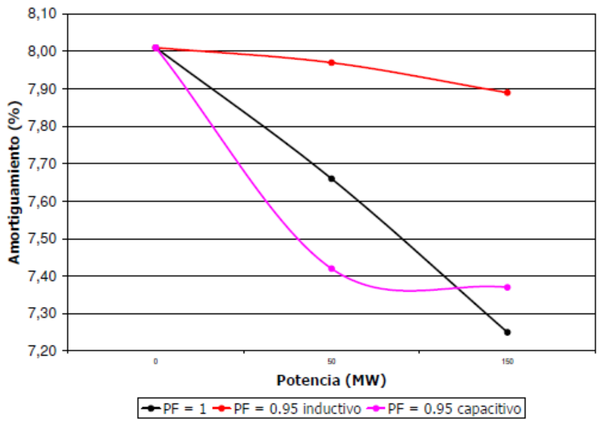

Figure 4: RN damping with increasing wind power

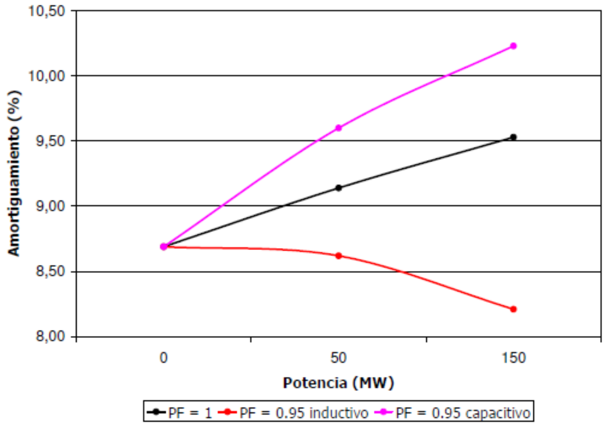

Figure 5: BY-T damping with increasing wind power

The exception to this is observed in the last point of active power (150MW) of Figure 3 due to a change in the pattern of oscillation caused by an increase of the participation factor of Punta del Tigre. More details are provided in [2].

V. GRAPHICAL ANALYSIS OF THE IMPACT OF WIND FARMS ON COMMON MODES (RN)

The impact of wind farm power injection on RN oscillatory mode can be explained with the aid of Figure 6, where a phasor diagram of Terra power plant is plotted, with (blue) and without (black) the inclusion of wind farms. It is supposed that Terra active power output remains constant:

1. The voltage at the busbar in Terra, must remain constant, regardless the amount of wind power injection. This is manifested through the increasing of internal angle of the generators of Terra. This will decrease the damping torque and synchronizing torque simultaneously, as it can be seen in Figure 4.

2. Additionally, a decrease of the reactive power output from Terra will be observed, as long as less reactive power is needed to maintain the busbar voltage in its nominal value. This situation will also induce the increasing of the internal angle, decreasing damping and synchronizing torques.

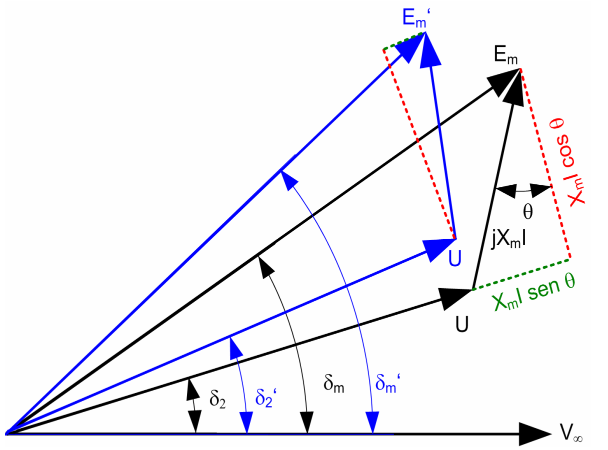

Figure 6: Phasor diagram of Terra with and without wind power

3. In accordance with the previous statement, if reactive power is injected by Terra due to reactive power consumption in Palmatir, the internal angle will decrease improving the synchronizing and damping torque.

4. The opposite is also true, it can be observed that reactive power production in Palmatir will induce reactive power absorption in Terra increasing its internal angle, and decreasing the damping and synchronizing torques.

From these statements and the modal analysis performed, it can be concluded that when wind farms are located close to synchronous generators, they will tend to deteriorate the damping of common modes and the synchronizing torque, as long as the active power injected by them is increased. Also, to mitigate this undesirable effect it is suggested that the wind farm absorbs reactive power, inducing an increase in damping and synchronizing torques.

VI. MATHEMATICAL ANALYSIS OF THE IMPACT OF WIND FARMS ON COMMON MODES (RN) AND INTERAREA MODES (BY-T)

To provide a mathematical explanation of the damping of common and interarea oscillatory modes, it will be used the simplified system represented in figure 1 in which the inertia and the damping of both machines are supposed to be the same. The swing equations of the synchronous generators are linearized in an operating point:

$$\begin{aligned} M\ddot{\delta}_s + D\dot{\delta}_s &= -k_{s1}\delta_1 - k_i\left(\delta_1 - \delta_2\right) = -k_1\left(\delta_s - \delta_1\right) \\ M\ddot{\delta}_m + D\dot{\delta}_m &= -k_{s2}\delta_2 - k_i\left(\delta_2 - \delta_1\right) = -k_2\left(\delta_m - \delta_2\right) \end{aligned} \tag{1}$$

Where:

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

To make simpler the analysis it will be supposed that:

$$\begin{aligned} k &= k_1 \approx k_2 \\ k_s &= k_{s1} \approx k_{s2} \end{aligned} \tag{3}$$

Furthermore, it is assumed that the term k_i is relatively small compared to k and k_S to represent the situation of a weak tie that interconect two generation areas. This will allow to express the swing equations in a simple form:

$$\begin{aligned} M\ddot{\delta}_s + D\dot{\delta}_s + \frac{kk_s}{k_s + k}\delta_s - k_i\left(\frac{k}{k_s + k}\right)^2 \delta_m = 0 \\ M\ddot{\delta}_m + D\dot{\delta}_m + \frac{kk_s}{k_s + k}\delta_m - k_i\left(\frac{k}{k_s + k}\right)^2 \delta_s = 0 \end{aligned} \tag{4}$$

This system can be expressed in a decoupled form if the following change of variables is made:

$$\begin{aligned} \theta_1 &= \delta_s - \delta_m \\ \theta_2 &= \delta_s + \delta_m \end{aligned} \tag{5}$$

$$\begin{aligned} M\ddot{\theta}_1 + D\dot{\theta}_1 + \frac{kk_s(k_s + k) + k^2 k_i}{(k_s + k)^2}\theta_1 = 0 \\ M\ddot{\theta}_2 + D\dot{\theta}_2 + \frac{kk_s(k_s + k) - k^2 k_i}{(k_s + k)^2}\theta_2 = 0 \end{aligned} \tag{6}$$

In this case, the modal variable θ_1, represents the response of the interarea mode (BY-T) and θ_2 represents the response of the common mode (RN). The following analysis will take into account equations 4 and 6. These equations will provide the neccesary information to explain the behaviour of the mode dampings analyzed in figures 4 and 5.

A. Impact of wind farms on interarea modes (BY-T)

As was stated, the active power injection will increase the angles of the system. In that case, k and k_S will suffer a reduction that will decrement the power exchange between the synchronous generators. This effect will improve the damping of interarea oscillation modes, particularly the damping of BY-T in this case. Furthermore, the incidence of reactive power exchange between wind farms and synchronous generators on interarea damping can be analyzed in equation 3. Given an active power output, if the wind farm begins to absorb reactive power, this reactive power must be generated by Terra to preserve the voltage in its busbar. This will induce an increment on k, which benefits the exchange of kinetic energy between the synchronous generators and consequently, the damping of interarea mode (BY-T) decreases. If the wind farm injects reactive power, the opposite effect takes place, the exchange of kinetic energy decreases and the mode damping increases.

B. Impact of wind farms on common modes (RN)

When a wind farm injects active power, the modal variable θ_2, will exhibit an important decrement on its synchronizing torque due to the marked reduction of the term $-k^2k_i$. This will lead an increment in the internal angle of the equivalent synchronous generator of power plants Terra and Baygorria. If the wind farm absorbs reactive power, the term k^2 increases due to the production of reactive power in Terra, and consequently, the internal angle will decrease, providing a better performance in damping and synchronizing torques. If the wind farm injects reactive power, the opposite situation is valid, the mode damping and synchronizing torque will decrease.

C. Impact of wind farms on mode damping

From the previous sections, it is clear that the wind farms will deteriorate the common mode damping (and synchronizing torque) and benefit the interarea mode damping. From the physical reasons discussed, it is not possible to improve the damping of both oscillatory modes at the same time. Anyway, it should be noted that in power systems, the common mode is dominant in the transient response due to the initial conditions prior to any type of disturbance, hence, to improve the oscillatory behaviour of the power system, it is suggested to impose the reactive power consumption of the wind park, to improve the common mode damping and synchronizing torque. This is conditioned by the damping of the interarea mode, and the capability curve of the synchronous and wind generators.

VII. TRANSIENT AND MODAL ANALYSIS

In order to validate the analysis performed, it was evaluated the system response when subjected to a three phase shortcircuit self cleared in 100ms in the line Terra-Young. Figures 7 and 8, shows of the internal angle of Terra and Baygorria for different scenarios:

- **Scenario 1:** Base case, without wind power.
- **Scenario 2:** Identical to scenario 1, but with wind power injecting nominal active power and without exchanging reactive power with the grid.
- **Scenario 3:** Identical to scenario 2, but with wind farm absorbing reactive power (power factor 0.95).

- **Scenario 4:** Identical to scenario 2, but with wind farm injecting reactive power (power factor 0.95).

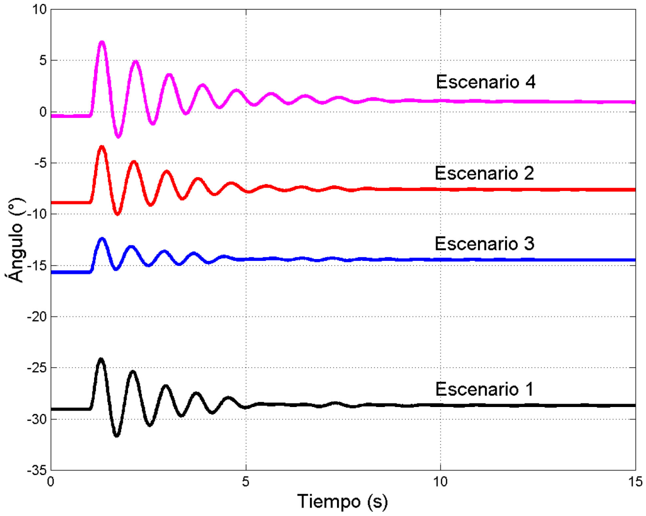

Figure 7: Internal angle - Terra

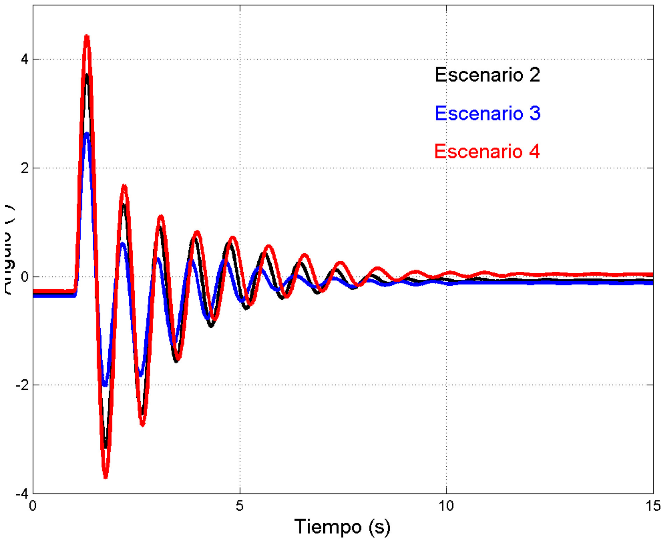

Figure 8: Internal angle - Baygorria

Also, it was performed the modal analysis for the scenarios descripted. The evolution of the damping of the modes RN and BY-T are showed in table 4.

Mode/Scenario	1	2	3	4
RN	8.01%	7.64%	7.95%	7.37%
BY-T	8.69%	9.18%	8.63%	9.68%

Table 4: Damping evolution of modes RN and BY-T

Both analyses show that RN mode damping decreases when wind power is included and BY-T damping increases. In scenario 3, it is shown an improvement in the oscillatory behaviour of RN, while the damping worsens in scenario 4, if it is compared with scenario 2. The opposite is true when BY-T oscillation mode is considered.

VIII. CONCLUSIONS

1. The impact of wind generation is highly dependent on the relative location between synchronous generators, wind farms and major load centers. When wind farms are electrically interconnected at points near synchronous generators tend to degrade the damping torque and synchronizing torque that characterize the local oscillatory modes. Moreover, if the wind farms are placed away from the synchronous machines, feeding local loads, they will tend to decrease the power transfer of synchronous generators, improving the damping and synchronizing torque.

2. If wind farms are installed in the vicinity of power plants, as in the case of Baygorria and Terra, the damping of the common mode, in which both plants are oscillating in phase with the rest of the power system, is degraded when power injection of the wind farm rises. Moreover, the damping of the interarea oscillation mode, which reflects the oscillation of each plant to the other, is increased.

3. In cases such as those described in the previous paragraph, this pattern is consistent: the incorporation of wind power tends to degrade the damping of the common modes and to enhance the damping of the interarea modes.

4. Due to the nature of the control system implemented in wind farms is not possible to simultaneously improve the two modes of oscillation, unless structural changes are made, including a power system stabilizer, for example.

5. Since the common modes are dominant in the dynamic response of power systems after sever disturbances, the degradation of them can be mitigated or even improved through the imposition of operating restrictions on wind farms. Particulary, reactive power consumption of certain wind farms will induce increased synchronizing torque in synchronous generators located close to them. In return, the reactive power exchange will be limited by the degradation of the interarea mode damping; therefore, it must be find a compromise to improve the performance of synchronous generators oscillations against severe disturbances without compromising the interarea mode damping.

IX. REFERENCES

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