

POWER SYSTEM STABILIZER CONTROL FOR WIND POWER TO ENHANCE POWER SYSTEM STABILITY

José Luis Domínguez-García

Electrical Engineering Area
IREC
Spain
jldominguez@irec.cat

Oriol Gomis-Bellmunt

CITCEA-UPC
gomis@citcea.upc.edu
and
IREC
ogomis@irec.cat

Fernando Bianchi

Electrical Engineering Area
IREC
Spain
fbianchi@irec.cat

Andreas Sumper

CITCEA-UPC
sumper@citcea.upc.edu
and
IREC
asumper@irec.cat

Abstract

The paper presents a small signal stability analysis for power systems with wind farm interaction. Power systems have damping oscillation modes that can be excited by disturbance or fault in the grid. The power converters of the wind farms can be used to reduce these oscillations and make the system more stable. These ideas are explored to design a power system stabilized (PSS) for a network with conventional generators and a wind farm in order to increase the damping of the oscillation modes. The proposed stabilizer is evaluated by simulation using DigSilent PowerFactory ®.

Key words

DFIG, Eigenvalue Analysis, Oscillation Damping, Power System, PSS, Small Signal Stability

1 Introduction

The rapid increment of wind power generation is modifying the power system behavior. As consequence, power system stability concepts have returned to the first line of research. A power system is defined as the set of generation plants, transmission lines and distribution systems, which are needed for electricity systems. In particular, the paper focuses its study on generation power plants, mainly on wind power generation. Several studies have been developed to know if wind power generation is capable of improving the power system stability, and more specifically of increasing the damping of the system [Caliao, Ramtharan, Ekanayake and Jenkins, 2010].

First, it is important to remark that wind power by itself does not induce new oscillatory modes, because the generator concepts used in wind turbines do not engage in power system oscillations. For example, squirrel cage induction generator connected directly to the grid has intrinsically more damped oscillation modes [Slootweg and Kling, 2003]. Generators of the variable speed wind turbines are decoupled from the

grid by a power converter [Slootweg and Kling, 2003]. In a stability analysis it is important to define where the wind farm is located, what generator technology is used, and how strong is the power system where the wind farm is connected. The impact of wind generation under different voltage levels or in various penetration percents can cause a poor behavior of the power system [Thakur and Mithulananthan; Epingle, Stenzel, Pöller and Müller, 2005].

A squirrel cage induction generator connected directly to the grid helps to enhance the stability of the system [Sumper, Gomis-Bellmunt, Sudria-Andreu, Villafafila-Robles and Rull-Duran, 2009]. However, the contribution to the stability is limited. On the other hand, the variable speed wind turbines have a power converter which is controlled to deliver to the grid the desired active and reactive power [Gomis-Bellmunt, Junyent-Ferré, Sumper and Bergas-Jané, 2008]. Thus, the use of variable speed wind turbine has been suggested to make support to the grid due to its capability of the power regulation [Martinez, Joos and Ooi, 2009]. In this schemes, the control demands to the wind turbine a variation on the power delivery. This power variation modifies the power flow of the whole power system in order to damp the desired oscillation modes [Miao, Fan, Osborn and Yuvarajan, 2009; Hughes, Anaya-Lara, Jenkins and Strbac, 2006].

The aim of the paper is to propose a power control for wind turbines to damp the power system oscillation modes. This paper is organized as follows. In section II, an overview of power system stability concepts is introduced and the mathematical basis of small signal stability analysis are presented. Power system Stabilizer design is presented in section III. An example of power system with a wind farm is simulated and discussed in section IV. Finally, in section V, the conclusions are summarized.

2 Power System Stability

Power system stability can be defined as the ability to remain in equilibrium during normal operating conditions and to regain an acceptable equilibrium after being subjected to a physical disturbance with most system variables bounded [Kundur, Paserba and Vitet, 2003; Anderson and Fouad, 1977].

The stability responses of a power system can be classified as [Kundur, 2007]:

- Rotor angle stability, which is concerned with the ability of each interconnected synchronous machine of the power system to maintain or restore the equilibrium between the electromagnetic torque and the mechanical torque.
- Frequency stability, it is related with the capability of a power system to restore the balance between the system generation and the load, with minimum loss of load.
- Voltage stability, which is dependent on the capability of a power system to hold on in steady state, the voltages of all buses in the system under normal operating conditions and after a disturbance.

Depending on the fault, rotor angle stability is divided in two different groups as transient stability and small signal stability. A power system under a small disturbance is considered in small signal stability. A small disturbance can be, for example, minor changes in load or in generation on the power system. This paper is interested in small signal stability analysis.

Study of small-signal stability may result in two different response modes such as non-oscillatory or aperiodic mode due to lack of synchronizing torque, and oscillatory mode due to lack of damping torque. The aperiodic problem has been largely solved by the use of automatic voltage regulators (AVR) into the generators. Oscillation modes are usually canceled by means of Power System Stabilizers (PSS).

Oscillatory small-signal stability problems which must be taken into account are inter-area modes with frequency ranging from 0.1 to 0.7 Hz and local modes in the range from 0.7 to 2 Hz [IEEE/CIGRE Join Task Force, 2004; Basler and Schaefer, 2008].

2.1 Small Signal Stability

Power Systems are a non-linear dynamic systems usually described by a set of non-linear differential equations together with a set of algebraic equations, i.e.,

$$\begin{aligned}\dot{x} &= f(x, u) \\ y &= g(x, u)\end{aligned}\quad (1)$$

where $x=[x_1, x_2, \dots, x_n]^T$ is the vector of the state variables, $u=[u_1, u_2, \dots, u_m]^T$ is the vector of the system inputs, $y=[y_1, y_2, \dots, y_r]^T$ is the vector of the system outputs, and $f=[f_1(x, u), f_2(x, u), \dots, f_n(x, u)]^T$ and $g=[g_1(x, u), g_2(x, u), \dots, g_r(x, u)]^T$ are the vectors of non linear functions.

The differential equations come from the application of electrical laws to the generic electrical power system of a n-machine system which is represented in Figure 1. The transmission system is represented as a matrix using the node method, assuming it as a passive system. The loads connected between the network system and the neutral node are represented in the right side of the transmission system. The black circle represents the set of dynamic loads such as polynomial or ZIP model, exponential load model, piecewise approximation and frequency-dependent load model [Machowski, Bialek and Bumby, 2008]. The black rectangle represents the loads supposed static. They can be assumed static and thus represented as a constant admittances.

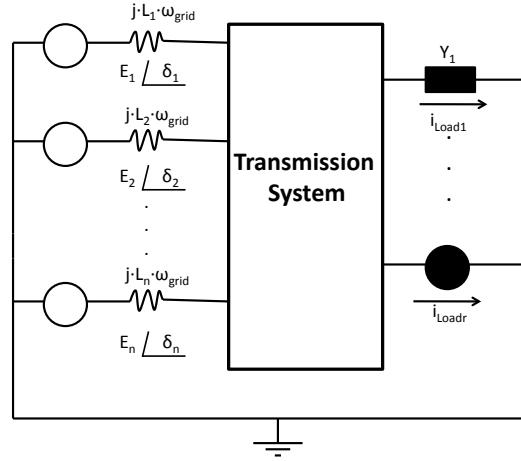


Figure 1. Representation of n-machines system

The transmission system including the static loads can be written as:

$$(I) = (Y)(E) \quad (2)$$

where (I) is the current vector, (E) is the voltage of the generators vector, and (Y) is the admittance matrix. The diagonal elements Y_{ii} and the non-diagonal elements Y_{ij} of the admittance matrix, which can be defined as,

$$\begin{aligned}Y_{ii} &= G_{ii} + jB_{ii} \\ Y_{ij} &= G_{ij} + jB_{ij}\end{aligned}\quad (3)$$

The electrical power injected into the network at node i, which is the electrical power output of the generator i, is described as:

$$S_i = P_{ei} + j \cdot Q_{ei} \quad (4)$$

where

$$\begin{aligned} P_{ei} &= \sum_{j=1}^n E_i E_j [B_{ij} \sin(\delta_i - \delta_j) + \\ &\quad + G_{ij} \cos(\delta_i - \delta_j)] \\ Q_{ei} &= \sum_{j=1}^n E_i E_j [G_{ij} \sin(\delta_i - \delta_j) - \\ &\quad - B_{ij} \cos(\delta_i - \delta_j)] \\ i &= 1, 2, \dots, n \end{aligned} \quad (5)$$

The generator equations of motion are given by:

$$\begin{aligned} \frac{2H_i}{\omega_{ref}} \frac{d\omega_i}{dt} + D_i \omega_i &= P_{mi} - P_{ei} \\ \frac{d\delta_i}{dt} &= \omega_i - \omega_{ref} \quad i = 1, 2, \dots, n \end{aligned} \quad (6)$$

The set of equations (5) and (6) is a set of n-coupled nonlinear second-order differential equations. Adding to these equations the electrical equations correspondent to the generators, the system described by (1) can be obtained. A deeper description about the system equations can be found in [Anderson and Fouad, 1977]. Since the small disturbance are considered, it is appropriate to linearize the system (1) around an operating point. Then, the power system can be written as a typical linear system.

$$\begin{aligned} \Delta \dot{x} &= A \Delta x + B \Delta u \\ \Delta y &= C \Delta x + D \Delta u \end{aligned} \quad (7)$$

where, Δ denotes a small variation from the operating point, A is the state matrix, B the input matrix, C the output coefficient matrix, and D is a matrix describing the direct connection between the input and the output. The eigenvalues of the A matrix can be calculated to analyze the stability of the system (7). The eigenvalues are the roots of the system characteristic equation $\det(sI - A)$ where \det is the determinant. Then, according to Lyapunov's first method, the small signal stability of a nonlinear dynamic system is given by the roots of the characteristic equation [Kundur, 1994; Gallardo, 2009]. The eigenvalues are described as:

$$\lambda = \sigma \pm j \cdot \omega \quad (8)$$

The eigenvalues of the state matrix can indicate the system response in the following form:

1. When $\sigma < 0 \forall \lambda$, the system is asymptotically stable
2. When at least one of the eigenvalues has $\sigma > 0$, the system is unstable
3. When $\omega \neq 0$, the system has a oscillatory response
4. When $\omega = 0$, the system has a non oscillatory response

Therefore, from the evaluation of the eigenvalues it can be easily determined if the system is stable or unstable and also if the power system may present any type of oscillation.

Moreover, the damping ratio $(\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}})$ permits to state how damped are the system oscillation modes.

3 PSS Design

The main function of power system stabilizer is to damp low frequency oscillations. This control device is designed to extend stability limits modulating the generator excitation. These oscillations typically occur in the frequency range of approximately 0.1 to 2.5 Hz, such modes are known as inter-area or local modes [Larsen and Swann, 1981].

Commonly, a PSS consists of four blocks as Figure 2 shows. The block T_m is the transducer emulator, the block T_w is the high pass filter, the block T_{ph} is the phase compensator and the last block is the output limiter.

The PSS input can be any signal affected by the oscillations of the synchronous machines. However, it is normally used the machine speed, the terminal frequency or the power. The output signal is usually a voltage variation in the excitation system.

The T_m block is the transducer emulator and models the delay effect introduced by the sensor.

$$T_m(s) = \frac{1}{1 + s\tau_m} \quad (9)$$

where the time constant τ_m , mainly in Europe, is set in 20ms.

This block can be usually neglected in order to reduce calculations.

The block T_w is a high pass filter that rejects the low frequencies of the input. The PSS is expected to respond only to transient changes.

$$T_w(s) = \frac{s\tau_{wh}}{1 + s\tau_{wh}} \quad (10)$$

The selection of the Washout time constant value (τ_{wh}) depends on the type of modes under study, p.e if τ_{wh}

is set at 4s, the system filters everything lower than 0.04Hz.

The dynamic compensator T_{ph} consists of a constant gain and a phase compensator. It provides the desired lead or lag phase; in order to reduce rotor oscillations. This dynamic compensator is usually made up of two lead-lag stages.

$$T_{ph}(s) = \frac{K_{PSS}(1 + s\tau_1)(1 + s\tau_3)}{(1 + s\tau_2)(1 + s\tau_4)} \quad (11)$$

The gain (K_{PSS}) determines the amount of damping introduced by the PSS. The time constants are selected in order to provide a phase lead in frequencies of interest.

Finally, the limiter is included to prevent the output signal of the PSS from exceeding the excitation system.

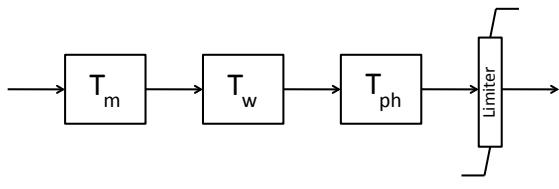


Figure 2. PSS basic scheme

3.1 PSS for Wind Turbine

To design the power system stabilizer control for wind turbine, it must be taken into account that wind power does not introduce new oscillation modes to the power system. Moreover, if the wind farm is connected into the grid too far from synchronous generators, it is not possible to attenuate local modes in the synchronous generators. Therefore, it is interesting to have a good knowledge about the power system under study and determine which rank of inter-area modes can be corrected.

The design of the control for wind turbines is based in the power system stabilizer scheme previously presented. However, the inputs and the outputs can be different. As it is previously mentioned, the input can be any signal affected by the oscillation. This fact implies the selection of the point common coupling (PCC) as measurement point, in order to avoid the filtering effect introduced by the transformer which is connected between the grid and the wind farm. The output can be any variable capable of varying the power delivered to the grid such as the active or reactive power, the generator slip or the excitation voltage. Actually, the PSS introduces small variations referred to the nominal values of the previously mentioned

values.

4 Power System Simulation

The power system under study is a 4-bus system as it can be seen in the figure 3. In the bus 1, one synchronous generator and one load are connected. The synchronous machine generates 150 MW of active power, and the load consumes 60 MW of active power and 20 Mvar of reactive power. One load is connected to the bus 2 in which active and reactive power consumption is 100 MW and 60 Mvar, respectively. In the bus 3, one synchronous generator and one load are added. Although, in this case, the generator delivers 40 MW of active power to the grid, and the load uses 45 MW of active power and 20 Mvar of reactive power. A wind farm is coupled to the bus 4 which generates 60 MW of active power, simulating 30 variable speed wind turbines. Finally, the slim lines in figure 3 represent the connection lines between the buses. All of them, are defined as a line with a 100 km of length and $0.153 + j \cdot 2\pi 50 \cdot 0.397887 \Omega/\text{km}$.

The system have been analyzed in four different case studies. First, is analyzed the grid without PSS compensation under initial conditions and under faulty conditions. Then, the system with PSS is studied under both conditions. The fault is simulated as a reduction of the active power on one load.

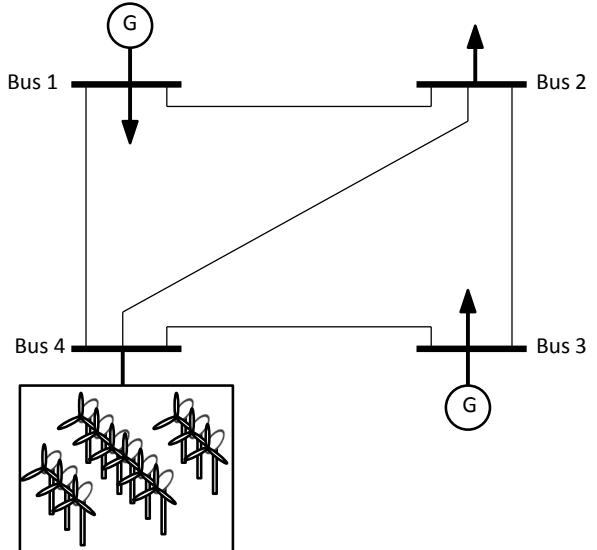


Figure 3. Power system under study

The PSS control applied to the wind farm uses the point common coupling (PCC) voltage as input and as output the active power reference.

The PSS is presented in the figure 4, the transducer block has not been included in this case. The time

constant T_w of the washout filter has been set 2 seconds. With this value, the filter allows to pass signals of frequencies higher than 0.08Hz, since the inter-area modes are in the range from 0.1 Hz to 0.7 Hz.

T_{ph} is implemented as a gain and one phase lead stage. The gain constant K_{PSS} has been set in 5, and the time constants T_1 and T_2 are 0.5 and 1.5 seconds, respectively. With these parameters, the phase lead is introduced in the frequency ranging between 0.1 and 0.3 Hz. Finally, the limiter is also included to limit the output signal between -0.05 and 0.05, (the values in per unit (p.u.)).

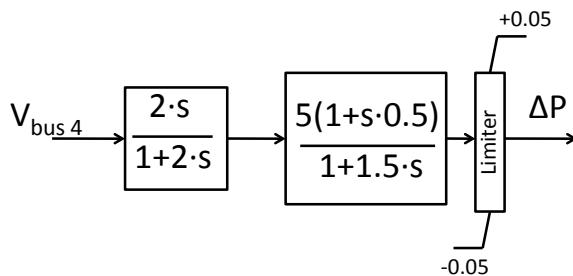


Figure 4. PSS control for wind turbines used in simulation

4.1 Simulation without PSS

First, the system has been simulated without power system stabilizer in the wind farm to determine stability characteristic and the number of oscillation modes. This study case is analyzed in two different situations, as it has been explained before.

Pre-Fault The eigenvalues analysis of the power system under initial conditions produces the values show in table 1. These oscillatory modes have been plotted in figure 5. It can be seen that the power system has two inter-area oscillation modes (modes 5 and 6) at the frequencies 0.358 and 0.104 Hz. The system has also two local modes, mode 3 and mode 4 are caused by the two synchronous machines. There are also two modes associated to the control.

In table 1, it can be observed that the real parts of all the eigenvalues have a negative value. Therefore, the system is stable. However, some eigenvalues are too close to the imaginary axis, and consequently the system may become unstable.

Post-Fault When a power demand variation occurs in the system, the dynamics is altered. In this situation, the eigenvalue analysis produces the values shown in table 2. These eigenvalues are also plotted in figure 6. Comparing the oscillation modes between table 1 and table 2, it can be observed that the oscillation mode

	ω_d (Hz)	ξ
Mode 1	6.481193	0.8194126
Mode 2	2.215764	0.03989288
Mode 3	1.735506	0.9751064
Mode 4	1.649494	0.0923488
Mode 5	0.3579988	0.9985647
Mode 6	0.1040641	0.8884763

	Eigenvalues
Mode 1	-58.21409 ± 40.72254
Mode 2	-0.5558333 ± 13.92205
Mode 3	-47.95331 ± 10.90451
Mode 4	-0.9612181 ± 10.36407
Mode 5	-41.93748 ± 2.249373
Mode 6	-1.265865 ± 0.6538542

Table 1. Most relevant oscillatory modes on initial conditions and without PSS

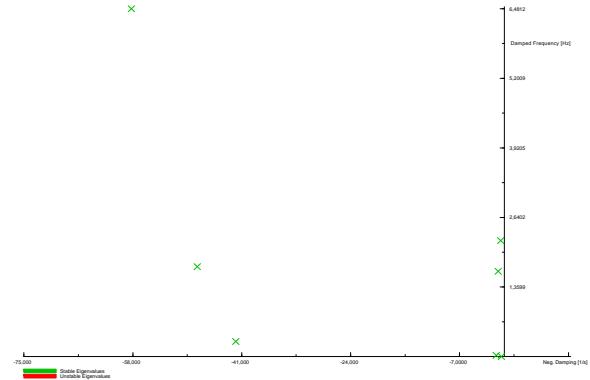


Figure 5. Representation of the oscillation modes without PSS and on initial conditions

5 in table 1 has been banished due to the new power flow. The control mode 1 has increased its oscillation frequency. Again, the system is stable moreover the eigenvalues a little farther from the zero axis than in the former scenario.

Both situations are expected due to the reduction of the load demand cutting down the system stress.

4.2 Simulation with PSS

In order to evaluate the PSS the system is analyzed in the previously mentioned scenarios.

	ω_d (Hz)	ξ
Mode 1	9.272294	0.7500609
Mode 2	2.215711	0.04199555
Mode 3	1.764306	0.9616387
Mode 4	1.512812	0.08815949
Mode 5	0.1110638	0.882172

	Eigenvalues
Mode 1	-66.07236 ± 58.25954
Mode 2	-0.5851666 ± 13.93402
Mode 3	-38.8606 ± 11.08546
Mode 4	-0.8412562 ± 9.50528
Mode 5	-1.307229 ± 0.6978342

Table 2. Most relevant oscillatory modes under faulty conditions and without PSS

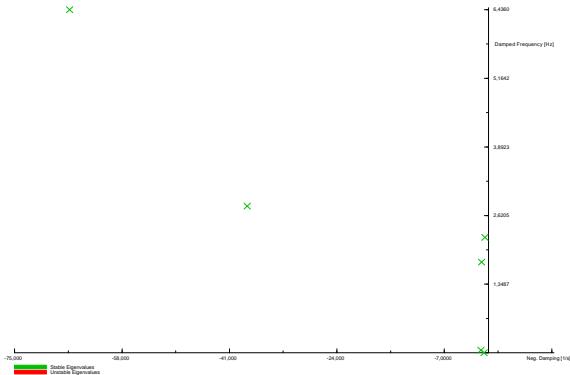


Figure 6. Representation of the oscillation modes without PSS and under faulty conditions

Pre-Fault Analyzing the oscillation modes of the table 3, it can be seen that the power system stabilizer has filtered the inter-area oscillation mode 6 as expected, since this mode is in the attenuation band [0.1-0.3Hz] of the PSS. The rest of the oscillation modes remain approximately without changes.

Post-Fault The eigenvalues for this case are listed in table 4. It can be seen that none inter-area oscillation mode remains. One inter-area mode has been filtered by the PSS control as in the previous case. Whereas the other one has been banished due to the new power flow. It is also interesting to notice that, in this scenario, the frequency of the oscillation modes associated to the control has not increased as it occurs in the same scenario but without PSS.

Comparing the eigenvalues in table 4 with the eigen-

	ω_d (Hz)	ξ
Mode 1	6.486656	0.8189943
Mode 2	2.167168	0.06070393
Mode 3	1.728199	0.9752866
Mode 4	1.654551	0.08615576
Mode 5	0.3598029	0.9985495

	Eigenvalues
Mode 1	-58.17279 ± 40.75686
Mode 2	-0.8281157 ± 13.61672
Mode 3	-47.93193 ± 10.8586
Mode 4	-0.899005 ± 10.39585
Mode 5	-41.9275 ± 2.260709

Table 3. Most relevant oscillatory modes on initial conditions and with PSS

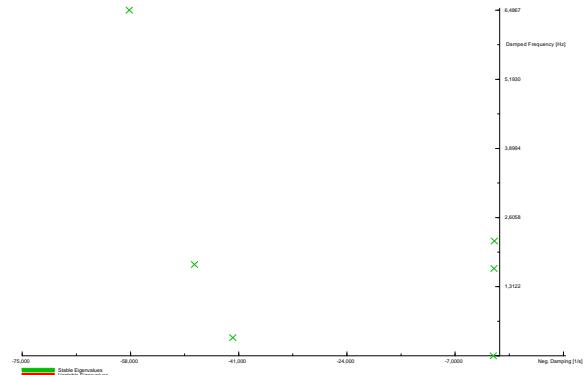


Figure 7. Representation of the oscillation modes with PSS and on initial conditions

values of those in table 2, it can be observed that in the case with PSS the system is more stable, since the real part of them are more negative.

	ω_d (Hz)	ξ
Mode 1	6.342678	0.8547192
Mode 2	2.810986	0.9094618
Mode 3	2.167638	0.06341672
Mode 4	1.757189	0.09017846

	Eigenvalues
Mode 1	-65.61948 ± 39.85222
Mode 2	-38.63239 ± 17.66195
Mode 3	-0.8654568 ± 13.61967
Mode 4	-0.9997108 ± 11.04075

Table 4. Most relevant oscillatory modes under faulty conditions and with PSS

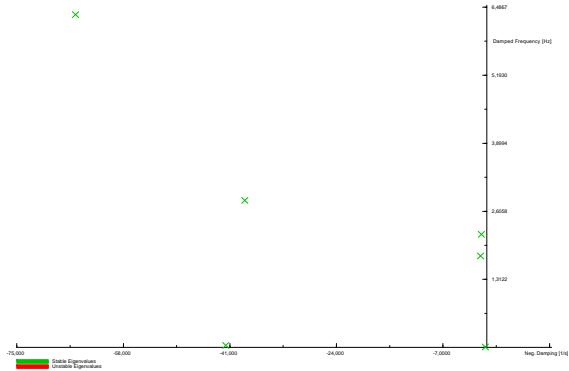


Figure 8. Representation of the oscillation modes with PSS and under faulty conditions

5 Conclusion

A brief overview of the power system stability oriented to the wind power integration in electrical networks has been presented. Wind farms may have the potential to contribute in the stabilization of the entire power system. To this end, PSSs are used to control the active and reactive power injected into the grid by the wind farms. These stabilizers can be designed using the same ideas than in conventional generation sources. To illustrate the application of PSSs in this context, a network consisted of three synchronous generators and a wind farm with a PSS has been analyzed. Four cases of study show the ability of the wind farms and the PSS to increase the damping of inter-area oscillation modes under normal operation and under fault in the grid.

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