Predicting, controlling and damping inter-area mode oscillations in Power Systems including Wind Parks

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Abstract: This paper shows a simple approach to predicting, controlling and damping inter-area mode oscillations. In the case of a stable operating point with a poorly damped oscillatory mode, the objective is to increase the damping of that mode. That is, the power system linearization at the operating point is modified. Operator actions such as redispatch, varying load, varying reactive power (voltage) often modify the operating point to do this; the effect of this is that transients near enough to the operating point will decay more quickly. However, the analysis does not attempt the more difficult study of large signal transients. The existence of a stable operating point is of course necessary for system security, but there is no guarantee that large signal transients will result in operation at that operating point. On the other hand, after carrying out some simulations, a methodology is built to predict eigenvalues.

Key-Words: Linearization, critical mode, eigenvalues, Wind Power Converter, damping, inter-area oscillations

1 Introduction
The power system may be thought of as a large, nonlinear system with many lightly damped electromechanical mode of oscillation. If the damping of these modes becomes too small or positive, then the resulting oscillations can cause equipment damage or malfunction [1].

Two prominent types of subsynchronous power oscillations are: interarea oscillations, power system areas swing against each other at frequencies of 0.1 Hz to 1 Hz. Local Oscillations, typically one plant swing against the rest of the system or several generators swinging against each other at frequencies of 1 Hz to 2 Hz. This work concentrates on inter-area oscillations

Inter-area oscillations are observed as oscillations of real power flow between regions of a power system or groups of generators [2]. Voltages and currents oscillate with the power swings. Sufficiently large oscillations trip, stress or can disrupt monitoring devices. In particular, oscillations can cause voltages to exceed limits causing protective devices to trip and forcing equipment outages.

Three ways in which oscillations can arise are:
1. Spontaneous oscillations, which arise when the mode damping becomes negative by a gradual change in system conditions; oscillations due to a disturbance, outage of a line or generator under unfavorable conditions can cause oscillations by suddenly reducing damping of a mode, and forced oscillations due to incomplete islanding or pulsating loads.

For the above reasons understanding oscillations and arriving at defensible and reliable ways to damp predict and control them are very important in power system including wind parks.

2 Test System
Models were implemented into PSS/E software package. The 9-bus test system has 3 generators, a Wind Park and 30 dynamic states, Figure 1.

![Figure 1. 9-bus Test System](image-url)
The 9 bus test system is essentially the WSCC system from the text of Sauer and Pai [3], some adjustment in loading and generation are carried out in order to create a critical. The generators are round rotor with d and q axis transient and subtransient effects represented. The exciters are IEEE type 1. For transient stability simulations, the real and reactive power portions of the load are typically modeled as constant current and constant admittance. The real power portions of the loads are modeled as 60% constant admittance and 40% constant current; the reactive power portions of the loads are modeled as 50% constant admittance and 50% constant current for buses 2, 5, 6 and 8. The load at bus 1 is modeled as constant power, active 100% and reactive 100%. The modeling of the variable-speed wind turbine is depicted in figure 2. The model consists of a block whose output is a wind speed sequence, the further blocks with a rotor sub-model. Their inputs are the wind speed, mechanical rotor speed and pitch angle, the torque exerted by the rotor and the current from the converter and the active and reactive power, respectively.

Besides, there are a number of additional blocks such as: A pitch angle controller, a rotor speed controller, wind speed model, and Wind power system stabilizer [4]. In order to damp power system oscillations, a control signal proportional to the deviation of the frequency is added to the real power reference, where \( \Delta f \) is the frequency deviation, \( P_{\text{dam}} \) is the proposed control signal, \( P_r \) is usual control and \( P_{w,\text{ref}} \) is the new real power reference. This control will actuate only during transient oscillations. During normal operation, when frequency deviation is null, the control signal \( P_{\text{dam}} \) will be zero.

\[
\frac{d\omega}{dt} = \frac{1}{2H} \left[ P_m - P_{\text{ref}} (1 + P_{w,\text{ref}}) \right]
\]  

(3)

3 Problem Formulation

3.1 State Space Model

To model the behavior of dynamic systems [5], quite often a set of \( n \) first order nonlinear ordinary differential equations are used. This set commonly has the form:

\[
\dot{x}_i = f_i(x_1, x_2, \ldots, x_n; u_1, u_2, \ldots, u_n; t) \quad i = 1, 2, \ldots, n
\]

(4)

Where \( n \) is the order of the system and \( r \) is the number of inputs. If the derivatives of the state variables are not explicit functions of the time, (1) may then be reduced to:

\[
\dot{x} = f(x, u)
\]

(5)

Where \( n \) is the order of the system, \( r \) is the number of inputs and \( x \), \( u \) and \( f \) denote column vectors of the form:

\[
x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix}, \quad f = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}
\]

(6)

The state vector \( x \) contains the state variables of the power system; the vector \( u \) contains the system inputs and \( \dot{x} \) encompasses the derivatives of the state variables with respect to time. The equation relating the outputs to the inputs and the state variable can be written as:

\[
y = g(x, u)
\]

(7)

The state concept may be illustrated by expressing the swing equation of a generator in per-unit torque as follows:

\[
\frac{2H \delta^2}{\omega_t} = T_m - T_e - K_D \Delta \omega_t
\]

(8)

Where \( H \) is the inertia constant at the synchronous speed \( \omega_t \), \( t \) is time, \( \delta \) is the rotor angle, \( T_m \) and \( T_e \) are the per-unit mechanical and electrical torque, respectively, \( K_D \) is the damping coefficient on the rotor and \( \Delta \omega_t \) is the per-unit speed deviation. Now, expressing (8) as two-first-order differential equations yields:

\[
\frac{d\Delta \omega_t}{dt} = -\frac{1}{2H} (T_m - T_e - K_D \Delta \omega_t)
\]

(9)

\[
\frac{d\delta}{dt} = \omega_t \Delta \omega_t
\]

(10)
3.2 Linearization
Small signal stability is the ability of the power system to maintain synchronism when subjected to small disturbances. In this context, a disturbance is considered to be small if the equations that describe the resulting response of the system may be linearized.

For the general state space system, the linearization of (5) and (7) about operating point \( \delta_0 \) and \( \omega_0 \) yields the linearized state space system given by:

\[
\Delta \dot{x} = A \Delta x + B \Delta u
\]

\[
\Delta y = C \Delta x + D \Delta u
\]

Here, \( \Delta x \) is the \( n \) state vector increment, \( \Delta y \) is the \( m \) output vector increment, \( \Delta u \) is the \( r \) input vector increment, \( A \) is the \( n \times n \) state matrix, \( B \) is the \( n \times r \) input matrix, \( C \) is the \( m \times n \) output matrix and \( D \) is the \( m \times r \) feed-forward matrix. Specifically, \( \Delta x = x - x_0 \), \( \Delta y = y - y_0 \), and \( \Delta u = u - u_0 \). As an example, (9) and (10) are linearized about the operating point \((\delta_0,\omega_0)\), yielding:

\[
\frac{d}{dt} \Delta \omega_r = \frac{1}{2H} (\Delta T_m - K_s \Delta \delta - K_p \Delta \omega_r) \quad (13)
\]

\[
\frac{d}{dt} \Delta \delta = \omega_0 \Delta \omega_r \quad (14)
\]

Where \( K_s \) is the synchronizing torque coefficient.

3.3 Eigenvalues and Stability Analysis
Once the state space system for the power system is written in the general form given by (11) and (12), the stability of the system can be calculated and analyzed. The analysis performed follows traditional root-locus (or root-loci) methods using PSS/E software package. First the eigenvalues \( \lambda_i \) are calculated for the \( A \)-matrix, which are the non-trivial solutions of the equation

\[
A \Phi = \lambda \Phi
\]

Where \( \Phi \) is an \( n \times 1 \) vector Rearranging (15) to solve for \( \lambda \) yields:

\[
\text{Det}(A - \lambda I) = 0 \quad (16)
\]

The \( n \) solutions of (16) are the eigenvalues \((\lambda_1, \lambda_2, \ldots, \lambda_n)\) of the \( n \times n \) matrix \( A \). These eigenvalues may be real or complex and are of the form \( \sigma \pm j \omega \). If \( A \) is real, the complex eigenvalues always occur in conjugate pairs.

The stability of the operating point \((\delta_0, \omega_0)\), may be analyzed by studying the eigenvalues. The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues appear on or to the right of this axis, the corresponding modes are said to be unstable, as is the system. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalues \( \lambda_i \), given by \( e^{\sigma t} \). The latter shows that a real eigenvalue corresponds to a non-oscillatory mode. If the real eigenvalues is negative, the mode decays over time. The magnitude is related to the time of decay: the larger magnitude, the quicker the decay. If the real eigenvalue is positive, the mode is said to have aperiodic instability.

On the other hand, the conjugate-pair complex eigenvalues \((\sigma \pm j \omega)\) each correspond to an oscillatory mode. A pair with a positive \( \sigma \) represents an unstable oscillatory mode since these eigenvalues yield an unstable time response of the system. In contrast, a pair with a negative \( \sigma \) represents a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that he desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

Other information that can be determined from the eigenvalues is the oscillatory frequency and the damping factor. The damped frequency of the oscillation in Hertz is given by:

\[
f = \frac{\omega}{2\pi} \quad (17)
\]

And the damping factor (or damping ratio) is given by:

\[
\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (18)
\]

4 Controlling by changing parameters
In case of a sustained oscillation, there is typically a power system equilibrium nearby that is oscillatory unstable. The objective is to stabilize this equilibrium by modifying the power system linearization at the equilibrium, which is now a stable operating point. This is a likely outcome, but other transient behaviors are possible. These work methods seek to stabilize the equilibrium to obtain an operating point that is sufficiently small signal stable and do not attempt to make more extensive changes to the system dynamics.

4.1 Producing an unstable case
The first task is to modify the base case for the 9 bus system including a Wind Park, and then compute the eigenvalues of the modified 9-bus power System, figure 3. On the other hand, it must fulfill the Spanish requirements and regulations such as: a wind park
power should not exceed 20 times the short circuit power in the point of common coupling.

In order to produce an unstable case that has oscillations, parameter variations were implemented simultaneously and the eigenvalues computed at each step, figure 4.

Starting from the unstable case, three ways to control and damp are analyzed.

4.1.1 Control by redispatch

The control by redispatch an oscillation shows that decreasing generator at bus 2 and/or bus 3 will move the unstable eigenvalue to the left, but decreasing generation at bus 2 is more effective. Figures: 5, 6 and 7.

4.1.2 Control by adding reactive load

The selection of reactive compensation controls to damp an oscillation is shown in the figures 8, 9, 10 and 11. It shows that adding reactive load at bus 2 and/or at bus 8 will move the unstable eigenvalue to the left but adding reactive load at bus 2 is more effective.
4.1.3 Control by changing bus voltage

In practice, the voltage at a generator bus would be changed by changing the voltage reference and the voltage at a load bus could be changed if a device as Static Var Compensator or Static Synchronous Compensator were installed.

It shows that increasing the voltage at generator bus 2 will move the unstable eigenvalue to the left. Figures: 12, 13 and 14.

5 Predicting eigenvalues

To predict eigenvalues, it is necessary to carried out some simulations for different power values; the number of power steps depend on the accuracy required. For instance, if the rated power of the generator 2 is 200 MW, it may be divided into 1, 2, 3, 4 or more steps in order to explain the methodology four steps have been selected (50,100,150,200 MW), but keeping constant the remaining parameters.

In this part, eigenvalues of the whole system are computed at each step, since two eigenvalues are two points, a lineal equations can be formed with each two eigenvalues and so it is possible to predict the new eigenvalues, fort that it is important to find out the intersection point of the straight line created by the power and the line created by the two eigenvalues, and then eigenvalues are projected toward the real axis and imaginary axis respectively, being obtained a prediction of all eigenvalues of the 9-bus power system. Figures: 15 and 16.

Where \( P_1 \) and \( P_2 \) are known active Powers and \( P_f \) is the new value of the Power at which the eigenvalues are projected. For instance, \( I_f \) and \( R_f \) are projected in order to get the Imaginary and Real part respectively.
6 Conclusion

It is apparent that loads have parameters that have much greater effect on the eigenvalue damping, if the load parameter is a limiting factor in ensuring power system stability, studies should be spent in order to more accurately determine parameters.

Control action can be taken to prevent oscillations, since eigenvalues calculations can distinguish lightly damped electromechanical mode of oscillation.

The same rules to predict eigenvalues can be followed if parameter variations are implemented simultaneously.

References:


