# A Small-Signal Stability Related Probabilistic Security Assessment of Wind Power Integration into Power Systems

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## Abstract

**In this paper, the impact of wind power generation in power systems on electromechanical oscillations is studied while both deterministic and probabilistic approaches are used. A probabilistic small signal security index is proposed to investigate the relationship between the probability of having poorly damped inter-area oscillations and the size of a wind farm to be interconnected with a power system network. This work includes small signal stability analyses performed on a two-area power system model involving two different types of wind turbine generators, squirrel-cage and doubly-fed induction generators.**

**Keywords:** Power system dynamics, small signal stability, power system security, wind power generation

## 1. Introduction

Utilizing renewable energy sources including the wind energy is becoming quite common in electric power generation. In the areas where wind energy can be considered as a significant source for electrical energy, power systems in which generation has been provided mostly by synchronous generators are now more subjected to large penetrations of wind turbine generators. Therefore, besides operational and planning aspects, the system dynamics which have been heavily related with synchronous generators is also under a drastic change as more induction machines or other types are used instead of synchronous generators.

Low frequency oscillations have been one of the important problems of interconnected power systems, especially, in which the areas are weakly connected or large power transmissions over long distances are desired. Damping of these oscillations, a classical small-signal stability problem, is traditionally carried out by using power system stabilizers or flexible ac transmission systems designed to operate in systems where generation is largely done by synchronous generators. This small-signal stability problem and the existing solutions are now to be studied from a new perspective considering the significant penetrations of wind power generators.

A considerable amount of work investigating the SSS problem with wind power penetration can be found in [2-7]. In the early work [7], it has been shown that, in some circumstances, penetration of wind power makes the system oscillations better damped. As it is observed in [2], the opposite may also be true depending on the topology of the network.

Wind power generation do not have a fixed and continuous level since it changes according to the wind speed. Therefore, the operating point changes due to generation as well as it changes due to consumption. As some other work that considers the uncertain characteristic of wind power generation, e.g. [8], can be found, it may become necessary to conduct probabilistic SSS analyses when we deal with integration of wind power generation into power systems.

This research is focused on the impact of wind power generation on the electromechanical power system oscillations and it uses a probabilistic SSS analysis method for dynamic security assessment. Probabilistic security indices considering small signal stability can be defined as in [9]. In our paper, the relation between the probability of having poorly damped inter-area oscillations and the size of a wind farm that is to be interconnected with an existing power system network is studied by a probabilistic security index defined. This work includes the studies when two different types of wind turbine generators, SCIG and DFIG, are projected to be integrated into a power system with a certain topology.

## 2. Background

### 2.1. Power System Dynamics and Small-Signal Stability Related Security

The quasi-stationary dynamics of a power system can be modeled by differential-algebraic equations. These equations contain differential equations associated with machine dynamics, any controller and actuator dynamics as well as stator and network algebraic equations.

When a small perturbation is assumed, the system can be linearised around an equilibrium and small signal stability analyses (SSSA) can be conducted. The reduced linearized dynamics can be represented by

$$\Delta \dot{u} = A \cdot \Delta u \quad (1)$$

where $A$ is the reduced Jacobian (system matrix) and the incremental changes in the state vector $u$ is denoted by $\Delta u$ .

The local dynamic behavior of the system is determined by (1), and the eigenvalues of $A$ , which satisfy the characteristic equation

$$\det( A - \lambda I )=0 \quad (2)$$

where $I$ is the identity matrix, define the modes of the local dynamic behavior. The linearized dynamics can be decomposed into its modes as in

$$\Delta u(t) = c_1 e^{\lambda_1 t} x_1 + c_2 e^{\lambda_2 t} x_2 + ...... + c_n e^{\lambda_n t} x_n \quad (3)$$

where $\lambda_i = \sigma_i \pm j\omega_i$ is an eigenvalue, $x_i$ is an eigenvector associated with $\lambda_i$ and $c_i$'s are the constants that depend on the initial condition, i=1, …, n [10].

Electromechanical oscillations are quite common in power systems especially when two or more areas are weakly connected and large power transmissions between the areas exist. Therefore, the electromechanical modes are the sources of high risk for instability and are considered to be critical. The damping ratio of a mode (eigenvalue) is defined as

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (4)$$

When damping of inter-area oscillation mode is lower than an acceptable value, the system is considered to be insecure.

## 2.2. Penetration of Wind Power

For a constant loading condition, small-signal stability analysis is performed generally on a single operating point. However, penetration of wind power generation results in an uncertainty of operating point due to the changes in the wind speed. Therefore, instead of analyzing a single operating point for a constant loading condition, small signal stability analysis is to performed over a range of operating points and probabilistic approaches would be more suitable.

As a common usage, the probability density of wind speed is formularized by Weibull probabilistic density function [11]. Weibull function can be defined as follows:

$$y = f(x) = ba^{-b} x^{b-1} e^{-(\frac{x}{a})^b} \quad (5)$$

where, a is the scale parameter; b is the shape parameter; x is a given wind speed; y is the probability density of the wind speed x [11].

If there is a suitable Weibull function for wind speed in a specific area, a set of random wind speeds can be generated from that function.

## 3. Methodology

In order to assess the small-signal stability of a power system involving wind power generation, the proposed methodology is based on a probabilistic approach.

A probabilistic security index considering the small-signal stability of a power system can be defined as the probability that all the critical modes have a damping ratio larger than an acceptable value $\varsigma_o$.

$$\eta = P(\varsigma_\lambda \geq \varsigma_o, \forall \lambda \in \sigma_{EM}(A)),\ 0 \leq \eta \leq 1 \quad (6)$$

where $\varsigma_\lambda$ is the damping ratio of an electromechanical mode associated with the eigenvalue $\lambda$ and $\sigma_{EM}(A)$ denotes the spectrum of the electromechanical eigenvalues of system matrix $A$.

Given a database of the wind speeds where the wind power generation is (or projected to be) penetrating into the system, a series of small-signal stability assessments (modal analyses) are conducted for a sufficiently large number of operating points changing due to the uncertainty in the wind power generation. The methodology starts with generation of proper Weibull functions that best describe the distributions of the wind speeds. The wind speeds sampled from the developed functions are, then, transformed into electrical power outputs of the wind farms that are integrated into the system.

The mechanical power of a wind turbine generator in a wind farm can be calculated from the wind speeds as follows:

$$P_m = \begin{cases} 0 & V_w \leq V_{cut-in} \\ 0.5 \cdot \rho \cdot A_{wt} \cdot C_p(\beta, \theta) \cdot V_w^3 & V_{cut-in} < V_w \leq V_{rated} \\ P_r & V_{rated} < V_w < V_{cut-out} \\ 0 & V_w \geq V_{cut-out} \end{cases} \quad (7)$$

where $P_m$ is the mechanical power extracted from wind; $\rho$ is the air density; $C_p$ is the performance (or power) coefficient, $\theta$ is the tip-speed ratio; $A_{wt}$ is the area covered by the wind turbine rotor; $V_w$ is the wind speed and $\beta$ is the blade pitch angle. [8]

For a projected power output of a wind farm, the operating point of the system can be determined through a power flow solution. Then, for each operating point, the small-signal security of the system can be studied by modal analysis in which the damping ratio of the least poorly damped electromechanical oscillatory mode is identified. Since a sample of a number of operating points varying due to uncertainty of the wind power generation in a system are created, an estimate of the probabilistic small-signal security index can be found based on this sample of operating points. This is simply done as we determine the ratio of operating points at which the damping ratio of all the critical modes are larger than $\varsigma_o$ = 5% to the total number of operating points in the same sample.

If a wind farm is to be integrated into an existing power network such that the system is maintained as secure in terms of small-signal stability, a method based on the probabilistic security index could be used.

The proposed method in this paper simply involves the calculation and comparison of the security index estimates for changing wind farm capacities. For example, if a continuous increase in the security index is observed for increasing wind farm capacities, as we have observed in our computations, the security index is calculated until a desired estimate for the probability of an acceptable damping in oscillations is achieved.

## 4. Simulation and Results

The proposed method is applied to a small test system consisting two areas each of which is composed of two aggregate models of synchronous generators that are equipped with power system stabilizers and a model of a wind farm that is planned to be integrated into one of the areas as shown in Fig. 1.

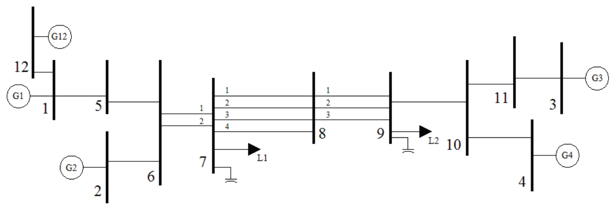


**Fig. 1.** Two area test system with wind power generation

An interchange power flow of 412 MW between the two areas, flowing from area A to area B, is projected to be met by a wind farm G12 and the synchronous generator G1 to be rescheduled. The generation and load levels in the test system are given in Table 1.

**Table 1.** Generator outputs and the constant loads

| G1+G12 (MW) | G2 (MW) | G3 (MW) | G4 (MW) | L1 (MW) | L2 (MW) |
|---|---|---|---|---|---|
| 412 | 967 | 719 | 700 | 967 | 1767 |

To investigate the effect of wind power generation replacing the power produced by the synchronous generator G1, a deterministic analysis is initially conducted where no uncertainty in wind power generation is assumed. The parameters associated with the wind and wind turbine are given in Table 2.

**Table 2.** The parameters associated with wind generation*

| | | | |
|---|---|---|---|
| $\rho$ (kg/m$^3$) | 1.2235 | $v_{cut-in}$ (m/s) | 3 |
| R (m) | 45 | $v_{cut-out}$ (m/s) | 25 |
| Cp | 0.473 | $v_{rated}$ (m/s) | 10.28 |

* Rated power of one wind turbine generator is 2 MW.

**Table 3.** Damping ratio of the inter-area mode for different levels of wind power penetration

| Operating Point | Wind G.(MW) | Synch. G.(MW) | Damping (SCIG) | Damping (DFIG) |
|---|---|---|---|---|
| **1** | 0 | 410.261 | 4.21% | 4.27% |
| **2** | 100 | 310.380 | 4.76% | 4.77% |
| **3** | 200 | 210.694 | 5.27% | 5.23% |
| **4** | 300 | 111.201 | 5.70% | 5.64% |
| **5** | 412 | 0 | 6.03% | 5.98% |

The damping of the inter-area oscillation is calculated and given in Table 3 for some levels of wind power penetration when either one of the two types of wind turbines (SCIG or DFIG) is used.

The loci and the trajectory of the eigenvalues associated with the inter-area mode are also given in Fig. 2.

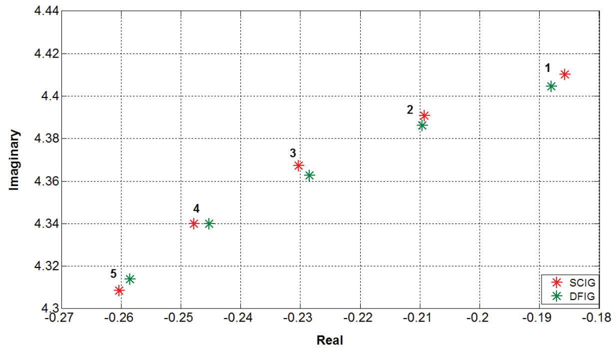


**Fig. 2.** Eigenvalues associated with inter-area oscillation mode in the complex plane

As can be seen from Table 3 and Fig. 2, as the contribution of the wind turbine generator, either SCIG or DFIG, to the inter-area power flow increases, the damping ratio gets larger and, thus, an improvement in damping of the inter-area oscillations is attained.

A better alternative to the deterministic approach above is studying the impact of wind farm integration by applying the probabilistic SSS analysis that accounts for the uncertainties in wind power generation. We suppose that the uncertainty in the wind speed is modeled by a proper Weibull distribution function (a=9.3058, b=2.6264) and the generation capacity of one wind turbine generator in the wind farm is 2 MW. The capacity of the wind farm is changed from 100 MW to 1000 MW with 100 MW steps and the probabilistic security is calculated for each capacity. At each step, the proposed eigenvalue analysis is conducted with 500 possible wind farm outputs to find an estimate for the probabilistic security index. The security indices when wind generation is provided by DFIGs or SCIGs are plotted in Fig. 3.

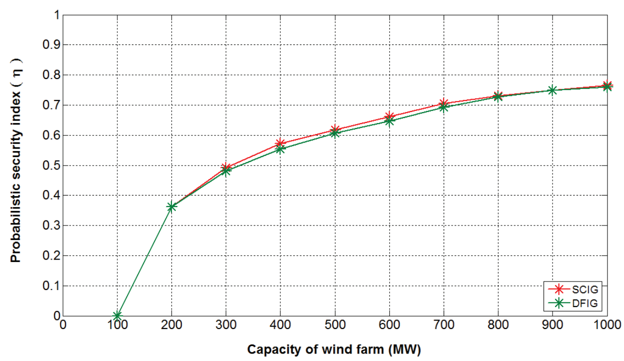


**Fig. 3.** Estimates for probabilistic security indices

As it can be seen from the figure, as the wind farm capacity increases, the probabilistic security index increases, that is, it decreases the probability of the damping ratio being below an acceptable value. For example, in order to maintain the probabilistic security index above 70%, a wind farm capacity greater than 700 MW is required. The power flow and SSS (eigenvalue) analyses are done by means of PSAT and SSAT which are parts of the software DSA*Tools*™ [12]. The probabilistic studies and the calculation of security index is conducted in the environment of MATLAB™.

## 5. Conclusions

Large penetrations of wind power generation into conventional interconnected power systems considerably impact the small signal stability of the whole system. Due to the uncertainties brought by the generation of wind power, probabilistic dynamic security analysis becomes necessary for better assessments. A probabilistic security index as defined in the paper can effectively be used for quantifying the risk of small-signal instabilities in the form of poorly damped oscillations.

It is observed that integration of wind turbine generators of certain type, SCIGs and DFIGs, has a beneficial effect on damping inter-area power oscillations. The effect of a wind farm's capacity in improving the small-signal security is notable. The results of this work show that increasing the capacity of the wind farm increases the security index defined in this work, i.e. the poorly damped inter-area oscillations become rare. The results are confined by power systems having a certain topology studied in the paper. However, they will continue to shed some light on the topic as new examples and tools are investigated in our future research.

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