UNCERTAINTY ANALYSIS OF THE IMPACT OF INTERMITTENT WIND GENERATION ON POWER SYSTEM OSCILLATIONS

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ABSTRACT
This paper studies the effects of wind power generation on power system small signal stability considering the intermittent characteristic of its primary energy source. The analysis is conducted using Monte Carlo simulation via modal analysis. Random samples are generated from Weibull distribution to obtain possible representative of wind speed needed for wind power generation using Latin hypercube sampling technique. Factors such as wind power integration level and wind farm location are considered in the assessment of the stability of a network interconnected by a weak tie-line. The oscillatory modes are calculated for each operating condition. The changes in modal characteristics of the system due to intermittent wind power generation are evaluated by observing the movement on the complex plane.

KEY WORDS
Monte Carlo simulation, Power system oscillation, Wind power, Latin hypercube sampling

1. Introduction

Wind energy as a sustainable source of energy has developed considerably in the past few years. This is as a result of liberation in the electricity market, advancement in wind power technology, energy supply security concerns and the policies on environmental issues [1]. However, this energy source exhibits variability in its output power. Up to now, wind power penetration is still low (20% maximum in Denmark), the ancillary services are mainly supported by the conventional power plants. When the penetration level is increased, issues regarding its impact on the power system network are important and need to be well understood. One of these issues is the possible impact on the power system small signal stability.

Small signal stability (SSS) results from insufficient damping of electromechanical oscillatory modes. These modes are of low frequency typically between 0.1–2 Hz [2]. Based on the frequency, electromechanical mode can further be classified into inter-area modes (0.1–0.8Hz) and local modes (0.8-2Hz). In the past, SSS was not much of concern, but with the increasing integration of wind power, it is now of great academic interest. Most wind resources are found very far from the city where access to strong grid is limited. The grid in this area is initially planned for unidirectional power flow [3]. Electricity from wind generators are mainly transmitted through weak and congested grid. Wind power may contribute negatively to power system damping under this circumstances.

The uncertainty in the behaviour of wind power is taken into account using Monte Carlo simulation via modal analysis. Random samples are generated from Weibull distribution to obtain possible representative of wind speed needed for wind power generation. Traditionally, simple random sampling is used to generate samples for the input variables in Monte Carlo-based uncertainty analysis. The problem with this method is that large size of samples is required to achieve reasonable results [4, 5]. A recent study shows that about 100 sample size generated from Latin hypercube sampling (LHS) is enough to produce reasonable results for practical purposes in probabilistic small signal stability applications [6]. This is found to improve the computational cost without jeopardizing the accuracy of the result. This is adopted in this paper. The change in the power system operating conditions due to fluctuating wind power can be regarded as a stochastic process. All variables involved in the process are random variables which can be accurately described by their expectation and the standard deviation (variance) [7]. Thus, expectation and standard deviation are used to describe uncertainty in the output variables in this paper.

The remaining part of this paper is organised as follows: Section two presents the probabilistic models of wind speed, wind turbine and the induction generator that are used to generate wind power. The power system model and the requirement for small signal stability analysis are presented in section three. The system under study is described in section four; the results are discussed in section five while the conclusion is presented in section six.

2. Probabilistic Model of Wind Speed, Wind Turbine and Induction Generator

2.1 Wind Speed Model

Two-parameter Weibull distribution is found suitable for modelling of wind speed of a given location [8]. It can be expressed by equation (1).
\[ f_W(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right] \]  

(1)

where \( f_W(v) \) is the probability of observing wind speed \( v \), \( k \) and \( c \) are the Weibull shape and scale parameters of the distribution respectively. The actual Weibull parameters of Napier in the coastal region of South Africa are used to generate the wind speed for the study [9].

2.2 Wind Turbine Model

The electric power \( P_{el(v)} \) of a pitch controlled wind turbine at different wind speeds \( v_i \) can be calculated using the turbine power curve. This power curve can be approximated with a parabolic equation as given in equation (2) [10].

\[
P_{el(v)} = \begin{cases} 
P_e \left( \frac{v_i^2 - v_{cl}^2}{v_r^2 - v_{cl}^2} \right) & (v_{cl} \leq v_i \leq v_r) \\
0 & (v_i \leq v_{cl} \text{ and } v_i \geq v_{co})
\end{cases}
\]

(2)

where \( v_{cl} \), \( v_r \) and \( v_{co} \) are the cut-in, rated and cut-out wind speeds respectively, \( P_e \) is the rated power, \( \eta_t \) is the overall efficiency and is given by \( \eta_t = \eta_m \eta_g \), the mechanical transmission efficiency is denoted by \( \eta_m \) and \( \eta_g \) is the generator efficiency. The parameters of wind turbine used in this study consisted of actual parameters of (VESTAS-V82). The specifications of the turbine can be found in [11].

2.3 Generator Model

The active power injected into the grid is derived from the power curve of the wind turbine with the prior knowledge of wind speed or its distribution. The reactive power absorbed from the grid can be derived using the steady state equivalent circuit of an asynchronous induction generator as shown in Figure 3.

\[
P_e(v_i) = \frac{-U^2 f_2}{s} + X^2
\]

(3)

where \( X = x_i + x_r \) and \( P_e(v_i) \) is the generated active power at different wind speeds according to the power curve in equation (2).
The amount of reactive power absorbed from the grid depends on the rotor slip \( s \) which also changes as the wind power varies in accordance to the wind speeds. From (3), \( s \) can be derived as (4)

\[
s_i = \frac{-U_r + \sqrt{U_r^2 - 4P_{e(i),vi}^2X_r^2}}{2P_{e(i),vi}X_r}
\]  

(4)

The reactive power \( Q_{(vi)} \) absorbed at different wind speed can be computed as (5)

\[
Q_{(vi)} = \frac{s_i^2(X + X_m) + r_i^2}{s_iX_m^2} P_{e(i),vi}
\]  

(5)

From the relation between active power and reactive power, different slip and reactive power can be obtained for different generated active power depending on the wind speed.

The active \( P_{e(i),wfi} \) and reactive power \( Q_{(vi),wfi} \) of a Wind Farm (WF) consisting of the same types of wind turbines can be expressed as equations (6) and (7), where \( N \) is the total numbers of wind turbines.

\[
P_{e(i),wfi} = NP_{e(i),vi}
\]  

(6)

\[
Q_{(vi),wfi} = NQ_{(vi)}
\]  

(7)

### 3. Power System Model and the Requirements for Small Signal Stability

Power system dynamic behaviour can be described by a set of differential and algebraic equation as given by (8)

\[
\begin{align*}
\dot{x} &= f(x,u,t) \\
y &= g(x,u,t)
\end{align*}
\]  

(8)

\( x \) is the state vector, \( u \) is the input vector and \( y \) is the output vector. For small signal stability analysis, equation (8) is linearised at the system’s equilibrium as (9)

\[
\begin{align*}
\Delta \dot{x} &= A \Delta x + B \Delta u \\
\Delta y &= C \Delta x + D \Delta u
\end{align*}
\]  

(9)

Subsequently, the system stability subject to small disturbance is studied based on the state matrix \( A \). The values of \( \lambda \) that satisfy equation (10) are the eigenvalues of matrix \( A \).

\[
\text{det}(\lambda I - A) = 0
\]  

(10)

They contain information about the response of the system to a small perturbation. The eigenvalue can be real or complex. The complex values appear in conjugate pairs.

\[
\lambda_i = \sigma_i \pm j \omega_i
\]  

(11)

The frequency of oscillation in, Hz, and the damping ratio are given by (12) and (13).

\[
f = \frac{\omega_i}{2\pi}
\]  

(12)

\[
\xi = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}
\]  

(13)

A mode is considered to be strongly damped if \( \xi \geq 5\% \), weakly damped if \( 0 < \xi < 5\% \) and poorly damped if \( \xi < 0 \).

### 4. System under Study

An IEEE 4–machine 13 buses system as shown in Figure 5 is selected for the study because it consists of two areas interconnected by a weak network. The synchronous generators are modelled as 4th order and equipped with IEEE type 1 exciter. The dynamics of power system stabilizer and turbine governor are neglected. The parameters of the system are provided in [12].

**Figure 5: IEEE 4 machines, 13 bus system**
Input N size time series average wind speed data at hub height generated using LHS

Generate output power using the power curve model and the corresponding reactive power

Set $i=1$

Perform load flow calculation using Newton Raphson algorithm

Calculate eigenvalues Via Modal analysis

$1 \leq N$ $i=i+1$

Statistical analysis of result

No

Yes

Figure 6: Flowchart of Monte Carlo–based probabilistic small signal stability

The impacts of wind power on the power system are studied under four scenarios (I–IV) and the results are discussed in section 5.

Table 1: Oscillatory mode in scenario I

<table>
<thead>
<tr>
<th>Modes</th>
<th>Eigenvalue</th>
<th>Damping ratio</th>
<th>Frequency</th>
<th>Type of modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7&amp;8</td>
<td>0.05 ± 3.90i</td>
<td>-0.01</td>
<td>0.62</td>
<td>Inter area modes</td>
</tr>
<tr>
<td>9&amp;10</td>
<td>-0.60 ± 7.25i</td>
<td>0.08</td>
<td>1.15</td>
<td>Area 2 local mode</td>
</tr>
<tr>
<td>11&amp;12</td>
<td>-0.57 ± 7.35i</td>
<td>0.08</td>
<td>1.17</td>
<td>Area 1 local mode</td>
</tr>
<tr>
<td>13 &amp;14</td>
<td>-8.20 ± 9.44i</td>
<td>0.66</td>
<td>1.50</td>
<td>Control mode</td>
</tr>
<tr>
<td>15&amp;16</td>
<td>-8.02 ± 9.84i</td>
<td>0.63</td>
<td>1.57</td>
<td>Control mode</td>
</tr>
<tr>
<td>17± 18</td>
<td>-5.4 ± 15.10i</td>
<td>0.34</td>
<td>2.40</td>
<td>Control mode</td>
</tr>
<tr>
<td>19&amp;20</td>
<td>-3.61 ± 17.38i</td>
<td>0.20</td>
<td>2.77</td>
<td>Control mode</td>
</tr>
<tr>
<td>24 &amp; 25</td>
<td>-37.26 ± 2.94</td>
<td>1.0</td>
<td>0.47</td>
<td>Control mode</td>
</tr>
<tr>
<td>31&amp;32</td>
<td>-98.36 ± 2.16</td>
<td>1.0</td>
<td>0.34</td>
<td>Control mode</td>
</tr>
</tbody>
</table>

Scenario I (Base case): This includes the original network without WF. This consists of four conventional synchronous generators (SG) as depicted in Figure 5.

Scenario II (WF connected to bus 20): WF consisting of 100 wind turbines (WTs) each having a rated power of 1.65MW (total of 165MW) is connected to bus 20. The wind power penetration at this bus is increased by increasing the number of WTs to 200, 300, 400 and 500WTs. This means that the rated power of the WF is increased from 165MW to 330, 495, 660 and 825MW respectively.

Scenario III (SG2 is removed and substituted by wind generator): Synchronous generator (SG2) on bus 2 is totally replaced by WF.

Scenario IV (The wind farm is shifted to Bus 120): The WF (100WTs) is now shifted from bus 20 to bus 120 with the four synchronous generators in service.

5. Results and Discussion

5.1 Scenario I (Base Case, No WF in the System)

A total of 35 eigenvalues were resulted after solving the load flow and performing the calculation of the eigenvalues and eigenvector of the system. There are 18 oscillatory modes of which 6 are electromechanical modes. The results of the oscillatory modes are presented in Table 1.

The interest of this paper is on the electromechanical modes. They are the modes that cause small signal instability in power systems if not properly damped. Inter area modes arise as a result of a group of generators in one area swinging against the group of generators in another area, in this case, SG1 and SG2 oscillating against SG3 and SG4. Local modes involve a group of generators in the same area swinging against each other. The system under study is found to have two local modes: Area 1 local mode which involves oscillation between SG1 and SG2 (mode 11& 12) and area 2 local mode in which SG3 is oscillating against SG4 (mode 9 & 10). All the modes are positively damped except the inter-area mode which has negative damping signifying that the system is small signal unstable. The inter-area mode determines the stability of the entire system. The plot of real and imaginary parts is shown in Figure 7.

The rotor angle plot of the generators involved in the inter-area mode and the speed participating factor (PF) plot is

Figure 7: Real and imaginary plots of scenario I
depicted in Figure 8. This is a confirmation that mode 7 & 8 is an inter area modes.

![Figure 8a: Rotor angle compass plot of the inter-area mode](image)

Figure 8b: Speed participating factor plot of the inter-area mode

![Figure 8b: Speed participating factor plot of the inter-area mode](image)

results of the mean damping ratio, mean frequency, mean participation factor and the corresponding probability of stability of the system as a result of wind farm consisting of 100 wind turbines connected to bus 20 is given in Table2. The results in the table show that the inter area modes is 100% unstable with a mean damping ratio of -0.0159 and standard deviation of 0.0036. The mean participation factor (PF) shows that SG1 has the highest contribution to the negative damping. Installation of power system stabilizer to this generator will provide the most effective damping of the mode. It can be seen that addition of wind generator to scenario 1 (base case) affects the damping of the inter-area and area 1 local mode negatively. The results of the mean participation factor in the table shows that wind generators do not contribute to the electromechanical modes but influence the damping of the modes.

The penetration of wind power on bus 20 was increased by increasing the numbers of wind turbines in the WF from 100 WTs to 200, 300, 400 and 500 WTs respectively. The resulting impact on the damping of the inter-area mode and the local modes are depicted in Figures 9 and 10 respectively. It can be seen from Figure 9 that wind power has a slight negative influence on the inter area mode as the WTs in the WF increases up to 400. However, when the WTs are further increased to 500, the damping of the inter-area mode improves. This might be due to a change in power flow imposed by large integration of wind power. Figure 10a shows that increase in wind power integrations at bus 20 has a negative impact on area 1 local mode. The modes decreases as the wind power increases. Increase in wind power penetration has little impacts on area 2 local

![Table 2: Scenario II (WF consisting of 100WTs connected to bus 20)](image)

<table>
<thead>
<tr>
<th>No of wind turbines and Modes</th>
<th>Mean damp $E(\xi)$</th>
<th>Std Dev Damp $\sigma(\xi)$</th>
<th>Mean Freq $E(f)$</th>
<th>Std Dev Freq $\sigma(f)$</th>
<th>Probability of stability</th>
<th>Mean speed participation factor (PF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% -ve damp</td>
<td>% Weak damp</td>
</tr>
<tr>
<td>100 WTs at Bus 20</td>
<td>-0.0159</td>
<td>0.0036</td>
<td>0.620</td>
<td>4.97x$10^{-4}$</td>
<td>100</td>
<td>0.0</td>
</tr>
<tr>
<td>9 &amp; 10 Area 2</td>
<td>0.0828</td>
<td>1.6x$10^{-4}$</td>
<td>1.155</td>
<td>7.52x$10^{-4}$</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>11&amp;12 Area 1</td>
<td>0.0691</td>
<td>0.0080</td>
<td>1.173</td>
<td>0.0023</td>
<td>0.0</td>
<td>4</td>
</tr>
</tbody>
</table>

5.2 Scenario II (WF connected to bus 20)

A wind farm consisting of 100 wind turbines each of rated power of 1.65MW is connected to bus 20. A total of 35 eigenvalues were obtained signifying that no additional modes are added or subtracted from the scenario I. The mode until the numbers of WTs increases to 500WTS when the mode begins to be affected negatively as shown in Figure 10b.
The wind power varies over a wide range from zero to the rated wind speed in accordance with change in wind speed. This causes a corresponding change in load flow and in the damping torque of the synchronous generation. The trajectory of the Area 2 local mode and the inter-area mode with different wind power integration is depicted in Figure 11. It can be deduced from the figure that the Area 2 local mode stability can be under threat at high wind power. It can also be seen that the instability of the inter-area mode is as a result of insufficient power generation. The inter-area mode is stable at high wind power.
5.3 Scenario III (SG2 is totally replaced by a wind generator)

The conventional synchronous generator (SG2) connected to bus 2 was totally removed and substituted with WF consisting of 100 WTs. After solving the load flow and calculating the eigenvalues and the eigenvectors, the numbers of states reduced from 35 to 25. The results of the electromechanical modes are presented in Table 3.

It can be observed from Table 3 that the area 2 local mode (oscillatory mode between SG1 and SG2) disappeared. This is because the generator (SG2) participating in this mode has been totally substituted with wind generator. The wind generator itself does not contribute to the electromechanical modes. The mean rotor angle plot and the mean speed participation factor plots of the participating generators in the inter-area mode are depicted in Figures 12 and 13. SG2 does not appear in both the mean rotor angle plot and the mean speed participating factor plot.

### Table 3: Results of the electromechanical modes with SG2 totally replaced with WF (100WTs)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Mean damp ( E(\xi) )</th>
<th>Std Dev Damp ( \sigma(\xi) )</th>
<th>Mean Freq ( E(f) )</th>
<th>Std Dev Freq ( \sigma(f) )</th>
<th>Probability of stability</th>
<th>Mean speed participation factor (PF)</th>
</tr>
</thead>
</table>
| 7&8     | -0.0516                | 0.0098                        | 0.7062                | 0.0037                      | 100                      | \( \omega_1 = 1.00 \)
|         |                        |                               |                       |                             |                          | \( \omega_2 = 0.0 \) \( \omega_3 = 0.55 \) \( \omega_4 = 0.35 \) |
| 9&10    | 0.0539                 | 6.8x10^{-5}                  | 1.1488                | 1.1x10^{-5}                 | 0.0                      | \( \omega_1 = 0.80 \)
| Area 2  |                        |                               |                       |                             |                          | \( \omega_2 = 1.00 \) |
| 11 & 12 | -                     | -                             | -                     | -                           | -                        | \( \omega_1 = 0 \) \( \omega_2 = 0 \) |
| Area 1  | -                     | -                             | -                     | -                           | -                        | -                                 |

5.4 Scenario IV (The WF is shifted to bus 120)

The location of the WF (consisting 100WTs) was changed to bus 120 with all the synchronous generators in service. The results of the electromechanical modes are presented in Table 4.

Comparing the results in Table 2 with the one in Table 4, an improvement in the inter area mode (mode 7 & 8) can be observed when wind farm is shifted to bus 120. The inter area mode has a positive mean damping of 0.076 with a high standard deviation of 0.2919 indicating that most of the damping ratio are far from the mean value. There is an improvement in the inter area mode with 9% chance of its being strongly damped compared to 0% probability when connected to bus 20. There is little impact on the area 2 local modes with mean damping ratio of 0.083 and standard deviation of 7.0x10^{-5}. The low standard deviation shows that this mode will be strongly damped for all operating states. However, the effects of wind power on area 1 local mode is slightly affected negatively when the wind generator location was changed to bus 120, the probability of this mode to be strongly damped reduced from 96% when connected to bus 20 to 93% when shifted to bus 120. This shows that the location of a wind generator can have both positive and negative impact on the small signal stability of a power system. While some modes are positively influenced some are also affected negatively.

![Figure 12: Mean compass rotor angle plot of the inter area mode.](image)

![Figure 13: Mean speed participating factor plot of the inter area mode.](image)
Table 4: The WF (100WTs) is shifted to bus 120

<table>
<thead>
<tr>
<th>No of wind turbines and Modes</th>
<th>Mean damp $E(\xi)$</th>
<th>Std Dev Damp $\sigma(\xi)$</th>
<th>Mean Freq $E(f)$</th>
<th>Std Dev Freq $\sigma(f)$</th>
<th>Probability of stability</th>
<th>Mean speed participation factor (PF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 WTs 7&amp;8 Inter area</td>
<td>0.076</td>
<td>0.2919</td>
<td>0.5588</td>
<td>0.1689</td>
<td>91 0.0 9.0</td>
<td>$\omega_1 = 0.66 \quad \omega_2 = 0.38 \quad \omega_3 = 0.91 \quad \omega_4 = 0.75$</td>
</tr>
<tr>
<td>9&amp;10 Area 2</td>
<td>0.083</td>
<td>$7.0 \times 10^{-4}$</td>
<td>1.154</td>
<td>$5.95 \times 10^{-4}$</td>
<td>0.0 0.0 100</td>
<td>$\omega_2 = 0.87 \quad \omega_4 = 1.00$</td>
</tr>
<tr>
<td>11&amp;12 Area 1</td>
<td>0.068</td>
<td>0.0092</td>
<td>1.173</td>
<td>0.0026</td>
<td>0.0 7.0 93</td>
<td>$\omega_1 = 0.83 \quad \omega_2 = 1.00$</td>
</tr>
</tbody>
</table>

6. Conclusion

The uncertainty analysis of the impacts of intermittent wind generation on power system oscillation using MCS with LHS has been presented in this paper. The results show that wind generator does not participate in the oscillation of a power system; however it influences the damping of the modes. It has been shown that the impacts of wind power on the damping can be positive or negative depending on the wind power integration and the location. While some modes are improved, some are negatively influenced. For example, connection of wind power on bus 120 improves the inter-area damping compared to bus 20 but has a slightly negative influence on mode area 1 local mode.

Future research will focus on allocation of power system stabiliser for damping of electromechanical modes based on probabilistic approach.

References