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On Small-Signal Stability of Wind Power System with Full-Load Converter Interfaced Wind Turbines

Thyge Knüppel, Vladislav Akhmatov, Jørgen N. Nielsen, Kim H. Jensen, Andrew Dixon, Jacob Østergaard

Abstract—Small-signal stability analysis of power system oscillations is a well established field within power system analysis, but not much attention has yet been paid to systems with a high penetration of wind turbines and with large wind power plants. In this paper an analysis is presented which assess the impact of full-load converter interfaced wind turbines on power system small-signal stability. The study is based on a 7 generator network with lightly damped inter-area modes. A detailed wind turbine model with all grid relevant control functions is used in the study. Furthermore is the wind power plant (WPP) equipped with a WPP voltage controller and comparisons are presented. The models of wind turbine and WPP voltage controller are kindly provided by Siemens Wind Power A/S for this work. The study is based on modal analysis which are complemented with simulations on the nonlinear system.

Index Terms—wind turbines, wind power plant, wind power plant controller, power systems, small-signal stability, modal analysis

I. INTRODUCTION

With the rapid development in installed capacity of wind power and with the increasing size of each installation, the role and impact of wind power on power system operation is changing. In 2008 in USA alone 8.5 GW of new wind power based generation capacity was installed which accounts for over 40% of the total capacity added in USA in 2008 [1]. In grid codes from some transmission system operators this development is already noted, given that large wind power plants (WPP) are termed power park systems [2], [3]. A number of factors such as network topography, generator excitation control, HVDC control, transmission line power flows, etc. [10]. Also, the presence of non-synchronous generation units reportedly can have an impact on the damping of inter-area oscillations. In [11]–[13] comparisons are presented of the influence on power system oscillations of WPPs based on fixed-speed induction generators (FSIG) and doubly fed induction generators (DFIG). In the studies it is generally found that FSIG WTs increase the damping of the power oscillations. References [11], [13] also report increased damping from the DFIG machine while [12] notes that the DFIG does not have any significant effect on the damping.

In [14] the influence is analyzed of the voltage/V AR control mode of DFIG based WPPs on inter-area oscillations. The study found that increasing the penetration of wind power generally had a favorable effect, with increased frequency and damping of the inter-area mode between a weak and a stronger system. With the WPP in voltage control mode [14] found that, for some parameter-set, an adverse interaction is noticed; it is, however, noted that these effects can be avoided with appropriate tuning of the voltage controller.

In [15], [16] a generic small-signal stability model is developed for fixed- and variable-speed WTs with corresponding collector and utility grid where the units are connected. The approach is based on sensitivity analysis and singular value decomposition.

A few publications have investigated the possibility of using variable-speed WPPs actively to damp power system oscillations [17]–[20]. In a recent PhD thesis by Elkington it is concluded that DFIG based WPPs can provide a positive contribution to damping of power system oscillations by adding an auxiliary controller [21].

In this paper the impact of full-load converter interfaced wind turbines on small-signal stability, e.g. participation in power system oscillations, is investigated. The system is analyzed for the WPP with and without WPP voltage con-
controller. The analysis is based on a 7 generator network, which illustrates some aspects of the dynamic behavior of the UK power system, namely inter-area oscillations between major areas of the system.

The paper is organized as follows. In section II the basis for the analysis is established with a description of modal analysis and power system oscillations. Section III presents the study case, the analyzed WT concept, and the base characteristics of the study case, while section IV presents the case studies performed and the results of the analysis. Finally, the discussion and conclusion are found in sections V and VI, respectively.

II. METHOD

Power system oscillations are inherent in interconnected power systems based on synchronous generators [22]. Power system oscillations and the application of eigenvalue analysis as means of analysis are well described in the literature, e.g. [10], [23]. Another approach is to base the analysis on signal processing of measured data [24]–[26]. When analyzing very large systems this measurement based approach has the advantage that it is not dependent on the accuracy of a large dynamic model.

A. Eigenvalue Analysis

The analysis is based on the nonlinear set of system equations, dynamic relations as well as network equations, which are linearized in an operating point to obtain a linear system in the classical state space form

\[
\dot{x} = Ax + Bu
\]
\[
y = Cx + Du
\]

(1)

where \(x^{n \times 1}\) is the state vector, \(u^{r \times 1}\) the input vector, \(y^{m \times 1}\) the output vector, \(A^{n \times n}\) is the system state matrix, \(B^{n \times r}\) the input matrix, \(C^{m \times n}\) the output matrix, and \(D^{m \times r}\) the feed forward matrix. To analyze the dynamic performance of the system in (1) it is often useful to perform a similarity transformation to diagonalize \(A\), i.e. decouple the system dynamics.

\[
A\phi_i = \lambda_i \phi_i, \quad \text{for } i = 1, 2, \ldots, n
\]

(2)

where the eigenvalue, \(\lambda_i\), is found as the solution of

\[
\det(A - \lambda_i I) = 0
\]

(3)

and where \(I^{n \times n}\) is the identity matrix and \(\phi_i^{n \times 1}\) the right eigenvector for the \(i\)th eigenvalue, also commonly referred to as the mode-shape for the \(i\)th mode. Similar to the formulation in (2), the left eigenvector is defined as

\[
\psi_i A = \lambda_i \psi_i, \quad \text{for } i = 1, 2, \ldots, n
\]

(4)

where \(\psi_i^{n \times 1}\) is the left eigenvector for the \(i\)th eigenvalue.

In compact notation for all \(n\) eigenvalues, the right and left eigenvector matrices are defined as

\[
\Phi = [\phi_1 \phi_2 \ldots \phi_n], \quad \Psi = [\psi_1^T \psi_2^T \ldots \psi_n^T]^T
\]

(5)

Further, for power system studies the eigenvalue matrices are usually scaled to satisfy \(\Psi \Phi = I\).

The right eigenvector, \(\phi_i\), describes how the activity of the \(i\)th mode is distributed on the \(n\) state variables, while the left eigenvector, \(\psi_i\), weighs the contribution of the \(n\) state variables on the \(i\)th mode. The entrywise product of \(\phi_i\) and \(\psi_i^T\) is thus a measure of the importance of the states within the individual modes and is referred to as the participation factors

\[
P_i = [\phi_1, \psi_1; \phi_2, \psi_2; \ldots; \phi_n, \psi_n]^T
\]

(6)

or in compact notation

\[
P = \Phi \otimes \Psi^T
\]

(7)

where \(\otimes\) denotes the entrywise product of two equal sized matrices, and \(B^{n \times n}\) is the participation factor matrix.

The eigenvalues provide important information on the dynamics of the system, i.e. the frequency and damping of any oscillations. If the \(i\)th eigenvalue is given as \(\lambda_i = \alpha \pm jb\), the natural frequency, \(\omega_n\), the damped frequency, \(\omega_d\), and the damping ratio, \(\zeta\), are defined as

\[
\omega_n = \sqrt{\alpha^2 + b^2} \left[\frac{\text{rad}}{\text{sec}}\right], \quad \omega_d = b \left[\frac{\text{rad}}{\text{sec}}\right], \quad \zeta = -\frac{\alpha}{\omega_n} [\text{-}]
\]

From classical control theory of continuous time systems, it is given that mode \(\lambda_i\) is asymptotically stable only if \(\alpha < 0\).

It should be remembered that power systems in general are nonlinear while the modal analysis is based on a linear approach. Thus, the results from the modal analysis are only valid in proximity of the linearization point and should be perceived as a snapshot of the dynamic system behavior. The method of normal forms offer a framework for extending the modal analysis to include higher order terms and thereby capture dynamics not captured by a linear model [27], [28]. This method is especially important for stressed, highly nonlinear power systems which are not accurately described by the linear approximation in (1). Other means of ensuring the validity of the linear analysis is to complement with nonlinear time-domain simulations after which the dynamic response is evaluated.

To gain deeper insight into the dynamic behavior of the system, a series of modal analysis is often conducted where certain system parameter(s) are gradually changed. Analyzing the movement of the eigenvalues in the complex plane reveals the influence of the varied parameter to overall system dynamics and small-signal stability.

B. Power System Oscillations

In an interconnected power system the speed of the synchronous generators will constantly adjust according to the imbalance between generation and demand, where a production surplus will cause overspeeding of the generators; and vice-versa. It must be noted that the applied governor control is to keep the synchronous speed, i.e. the nominal grid frequency within a required narrow range of operation.

Power system oscillations are typically divided into three areas depending on its global (or local) scale.

- **Inter-area oscillations** where a group of generators in one area oscillates against a group of machines in another area, typically \(f \in [0.1, 0.3] \text{ Hz}\)
- intra-area oscillations where a group of generators in one area oscillates against a group of machines in the same area, typically $f \in [0.4, 0.7]$ Hz
- local-area or intermachine oscillations involve generators which are located close to each other, typically $f \in [0.7, 2.0]$ Hz. This includes adverse interaction between equipment control systems.

Many factors, beside the frequency of oscillation, do, however, determine the nature of the oscillations, and the concepts of mode-shape and participation factor are used to correctly identify the source, nature, and significance of a mode.

III. STUDY CASE

A. Case Network

The study is based on the 18 node, 7 generator system depicted in Fig. 1, which furthermore consists of 6 loads, and an aggregated WPP with corresponding collector grid. The system represents a large network that has been reduced to a small number of nodes. In TABLE VIII the generator ratings, transformer reactances, and load distributions are given, while the synchronous machine dynamic data and the network parameters are given in TABLE IX and XI, respectively.

The network model has been developed in collaboration with National Grid as an extension of the three generator system presented in [11] to achieve a higher level of flexibility and numerical stability. The network model is tuned for a light load situation and the distribution of load and generation implies a southbound power flow of approximately 1 900 MW. Note that the model does not accurately represent particular aspects of the UK network, and hence should not be used to draw conclusions regarding the performance of this network. The developed model does, however, assist in the understanding of power oscillations between major areas of the UK power system.

B. Wind Turbine Technology

The WT concept for this study is a variable-speed, pitch controlled, full-load converter interfaced WT and is illustrated in Fig. 2 and further described in [29]. A block diagram showing the overall connections is shown in Fig. 3. The applied model is kindly provided by Siemens Wind Power A/S being a key market player of such variable-speed WTs.

The applied model includes:
- **Aerodynamic model.** A variable wind speed aerodynamic model which includes power coefficient with pitch angle and tip-speed ratio.
- **Shaft model.** Implements a two-mass model of rotor, gearbox, and generator.
- **Converter system.** The WT converter system comprises a generator side and a network side converter including all required control of the injected active and reactive power as well as DC link voltage control.
- **DC link.** Implements the link, including the DC capacitance, between the machine and the network side converter.
- **Fault ride through.** Monitors for system faults and shapes the current injection into the grid upon detection.

In the study, an aggregated WT model is used and the analysis thus only considers the main interaction between the power system and the WPP.

C. Wind Power Plant Collector Grid

The collector grid is modeled as a T-equivalent with the entire capacitance lumped as a shunt and with half the inductance and half the resistance as a series impedance on each side. For $P_{WPP} = 180$ MW the network parameters are...
given in TABLE X. The collector grid parameters are scaled according to the size of the WPP such that the same voltage profile is achieved, i.e.

\[ z_{scale} = \frac{S_{base}^B}{S_{base,WPP}} \quad R = z_{scale} R^B \]

\[ X_L = z_{scale} X_L^B \quad B_{C} = \frac{B_{C}^B}{z_{scale}} \]

where the superscript \( B \) refers to the values in TABLE X with \( P_{WPP} = 180 \text{ MW} \).

D. Wind Power Plant Voltage Controller

The WPP voltage controller is an outer, corrective controller that controls the voltage at the point of common connection (PCC) at the interface to the power system. The WPP voltage controller distributes voltage set-points to the individual WTIs based on the conditions at the PCC, where the WT voltage controller controls the voltage at the WT terminals according to its set-point.

The block diagram of the WPP voltage controller is shown in Fig. 4 and the relation to the WT system is shown in the block diagram in Fig. 3. The droop controller prevents chasing of adjacent units both controlling the voltage by dividing the responsibility between the units. Furthermore, the droop controller ensures that a predictable amount of reactive power is delivered for a given deviation from the nominal voltage. The applied model of the WPP voltage controller has been kindly provided by Siemens Wind Power for this analysis, although Siemens Wind Power does not necessarily apply exactly the same control.

\[ V_{WCCast} \]

\[ Q_{VCC} \quad \text{LP} \quad k_d \quad \text{PI} \quad V_{af} \]

\[ V_{WCCast} \]

\[ Q_{VCC} \quad \text{LP} \quad k_d \quad \text{PI} \quad V_{af} \]

![Block diagram of the WPP voltage droop controller. LP: Low-Pass filter, PI: PI-controller.](image)

The operation of the WPP voltage controller is dependent on the strength of the grid and the controller must be carefully tuned for the conditions at the PCC. For this analysis, a 4% droop, i.e. \( k_d = 0.04 \), is used and the WPP voltage controller is tuned to deliver 90% of its response within 1 second in a well-damped manner [30].

A simulation is presented in Fig. 5 where a step-change is applied to the set-point of the exciter of the nearby generator \( G_2 \). The shown step-response is with \( P_{WPP} = 504 \text{ MW} \). As shown in Fig. 4 the WPP responds in a fast and well-damped manner, delivering the scheduled reactive power within 1 second. The set-point change at \( G_2 \) inflicts a perturbation in the electromagnetic torque at \( G_2 \), noticed by the swing in delivered active power. For the WPP the reactive power output is increased without affecting the delivery of active power.

![Time simulation showing the response of the WPP voltage controller to a step on the voltage reference on \( G_2 \). \( P_{WPP} = 504 \text{ MW} \).](image)

E. Generator Models

The synchronous generators are modeled as round rotor machines using the standard RMS model. The generators are aggregated machines, each representing several smaller and larger generation units; the total capacity for each unit is given in TABLE VIII and the parameters for the dynamic model in TABLE IX.

Parameters for the synchronous machines with corresponding exciter- and PSS models are selected to represent the dominant unit type in each area. Furthermore is each generator equipped with a standard IEEEG0 governor. Parameters, exciter- and PSS models have kindly been provided by National Grid for this study.

F. Characteristics of Case Network

A list of dominant eigenvalues is given in TABLE I. Three lightly damped inter-area modes are present in the system, \( \lambda_{1-3} \); the modal characteristics are given in TABLE II and the mode shapes in Fig. 6. Furthermore are three voltage controller modes selected for closer attention, \( \lambda_{4-6} \), as the analysis will show that these modes are sensitive to the size of the WPP.

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( \omega_\lambda )</th>
<th>( \psi_\lambda )</th>
<th>( \zeta_\lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_1 )</td>
<td>( -0.275 \pm 3.10 )</td>
<td>0.493</td>
<td>0.558</td>
</tr>
<tr>
<td>( \lambda_2 )</td>
<td>( -0.658 \pm 6.26 )</td>
<td>0.997</td>
<td>0.105</td>
</tr>
<tr>
<td>( \lambda_3 )</td>
<td>( -0.643 \pm 8.83 )</td>
<td>1.41</td>
<td>0.073</td>
</tr>
</tbody>
</table>

TABLE I

QUALITATIVE DESCRIPTION OF DOMINANT EIGENVALUES.

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( \omega_\lambda )</th>
<th>( \psi_\lambda )</th>
<th>( \zeta_\lambda )</th>
</tr>
</thead>
<tbody>
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<td>( -0.643 \pm 8.83 )</td>
<td>1.41</td>
<td>0.073</td>
</tr>
</tbody>
</table>

TABLE II

CHARACTERISTIC FOR THREE INTER-AREA MODES IN BASE CASE WITHOUT WIND POWER.
In TABLE III are the participation factors for the inter-area modes shown for the generator rotor angle states. The mode shape for three inter-area modes, $\lambda_{1-3}$, are given in Fig. 6 where the characteristic $180^\circ$ displacement between oscillating groups of generators is seen. The characteristics of the inter-area modes given in TABLE I are determined from the participation factors in TABLE III and the mode shapes in Fig. 6.

### TABLE III
NORMALIZED ROTOR ANGLE PARTICIPATION FACTORS FOR THE INTER-AREA MODES $\lambda_{1-3}$ FOR THE SYSTEM WITH NO WIND POWER CONNECTED.

| State variable | $|p_1|$ | $|p_2|$ | $|p_3|$ |
|----------------|-------|-------|-------|
| $\delta (G_1)$ | 0.21  | < $10^{-2}$ | < $10^{-4}$ |
| $\delta (G_2)$ | 0.11  | < $10^{-2}$ | < $10^{-4}$ |
| $\delta (G_3)$ | < $10^{-2}$ | 0.01  | 0.01  |
| $\delta (G_4)$ | 0.03  | 0.28  | 0.07  |
| $\delta (G_5)$ | 0.04  | 0.02  | < $10^{-2}$ |
| $\delta (G_6)$ | 0.08  | 0.18  | < $10^{-2}$ |
| $\delta (G_7)$ | 0.01  | 0.02  | 0.42  |

The modal analysis is a linear method and it should thus be complemented with dynamic simulations on the nonlinear system. In Fig. 7 and 8 the dynamic response is shown after a three-phase short-circuit at line $l_{48}$. For now, there is no wind power in the system. The fault is applied midway between the busses, on a single circuit, and it is cleared after 140 ms. Fig. 7 shows the active and reactive power flow on the double circuit $l_{48}$ during and after the short-circuit. From the dynamic response the damping ratio, $\zeta$, and the damped frequency of oscillation, $\omega_d$, are computed as

$$\delta = \frac{1}{2} \ln \left( \frac{1294 - 1150}{1181 - 1150} \right) = 0.5119$$
$$\zeta = \frac{\delta}{\sqrt{\delta^2 + (2\pi)^2}} = 0.081$$
$$\omega_d = \left( \frac{1}{\delta} \left( 7.523 - 1.391 \right) \right)^{-1} = 0.49$$

The short-circuit excites inter-area oscillation $\lambda_1$ between $G_{1-2}$ and $G_{3-7}$, which is noted by the grouping of the generators in Fig. 8 where the generator rotor speeds are plotted, cf. mode shape plot in Fig. 6.

### IV. SELECTED CASES
The aim of the study is to analyze the influence of increased wind power penetration on power oscillations in the system, with emphasis on the previously mentioned inter-area modes. Two cases with a varying penetration of wind power are investigated and compared to the base case with only synchronous generation

1) $P_{sep}$ of $G_2$ is reduced as penetration of wind power is increased while the MVA rating is maintained

2) MVA rating of $G_2$ is reduced as penetration of wind power is increased while the loading of $G_2$ is maintained

In all cases and for all wind power penetration levels, active power production is shifted between only $G_2$ and the WPP and the power flow in the system is thus unchanged.

In case 1 the introduction of wind power does not displace any conventional units and only the active power set-point is reduced to accommodate the power produced by the WPP. While in case 2, the wind power displaces conventional units.
and the MVA rating of $G_2$ is reduced accordingly. In each case the size of the WPP is varied linearly from 36 to 1000 MW in 10 steps.

A. Local WT Voltage Control

When only local voltage control is employed in the WPP, the WTs control to achieve a voltage of 1 pu at the terminals.

The modal characteristics of the three selected inter-area modes, $\lambda_{1-3}$, are presented in TABLE IV for $P_{\text{WPP}} = 1000$ MW. When compared to the modal characteristics of the base case in TABLE II it is clear that the three inter-area modes are largely unaffected by the 1000 MW WPP.

![Fig. 9. System eigenvalues in the complex plane.](image)

**Fig. 9. System eigenvalues in the complex plane.**

The participation factors measure the participation of each state variable in the eigenvalues and how each mode is shaped. In TABLE V selected participation factors are listed for inter-area mode, $\lambda_1$; namely, generator rotor angle states and WPP mechanical generator, rotor, and shaft states. Furthermore is the largest participation over all WPP states given.

![Fig. 10. Comparison of selected system eigenvalues.](image)

**Fig. 10. Comparison of selected system eigenvalues.**

The maximum WPP participation is in both cases found in $\lambda_1$. The participation factors for the WPP mechanical states are orders of magnitude smaller than those of the synchronous generators; hereby implying that the WPP does not participate in the oscillation.

**TABLE V**

**COMPARISON OF SELECTED PARTICIPATION FACTORS FOR INTER-AREA MODE, $\lambda_1$, FOR CASE 1 AND 2. FOR THE WPP PARTICIPATION FACTORS ARE SHOWN FOR MECHANICAL GENERATOR-, ROTOR- AND SHAFT-ANGLE STATES, AND THE MAXIMUM PARTICIPATION OVER ALL WPP STATES.**

| State variables | $|\rho|$ case 1 | $|\rho|$ case 2 |
|-----------------|---------------|---------------|
| $\delta$ (G1)   | 0.22          | 0.28          |
| $\delta$ (G2)   | 0.10          | 0.05          |
| $\delta$ (G3)   | $< 10^{-2}$   | $< 10^{-2}$   |
| $\delta$ (G4)   | 0.03          | 0.03          |
| $\delta$ (G6)   | 0.04          | 0.03          |
| $\delta$ (G7)   | 0.08          | 0.07          |
| $\delta$ (WPP)  | 0.01          | 0.01          |
| $\delta_1$ (WPP) | $< 10^{-7}$ | $< 10^{-7}$   |
| $\delta_2$ (WPP)| $< 10^{-5}$ | $< 10^{-5}$   |
| $\delta_3$ (WPP)| $< 10^{-5}$ | $< 10^{-5}$   |
| $\max(|\rho|)$ (WPP) | $< 10^{-2}$ | $< 10^{-2}$   |

For case 1 with $P_{\text{WPP}} = 1000$ MW, the mode shapes are given in Fig. 11 for the generator speed states for the three inter-area modes, $\lambda_{1-3}$. The inter-area characteristics in terms of generator grouping are not significantly changed by the WPP. Similar mode shapes are obtained for case 2.

B. Wind Power Plant Voltage Controller

The modal characteristics of the three selected inter-area modes, $\lambda_{1-3}$, are presented in TABLE VI for $P_{\text{WPP}} = 1000$ MW and with WPP voltage controller. When compared to the modal characteristics of the case with only local WT voltage control in TABLE IV, it is clear that the three inter-area modes are largely unaffected by the WPP voltage controller.

A comparison of the eigenvalue movement as the wind power penetration increases from 36 to 1000 MW is given in Fig. 12; again only limited movement of the three inter-area modes are noticed. The mode shapes for the generator speed states for the three inter-area modes are given in Fig. 13 for
case 1 with $P_{\text{WPP}} = 1\,000$ MW. Similar results are obtained for case 2 where $G_2$ is gradually displaced.

In TABLE VII the participation factors are given for inter-area mode $\lambda_1$ for case 1 and 2. Similar results are found for inter-area modes $\lambda_2-3$. As noted in section IV-A the WPP participation in the oscillation is orders of magnitude smaller than for the synchronous machines. The largest participation factor for both case 1 and 2 is for the input filter for the PCC voltage measurement which is slightly larger than for the reactive current controller.

![Fig. 11. Mode shape for the generator speed state for three inter-area modes. The presented mode shapes are for case 1 with $P_{\text{WPP}} = 1\,000$ MW.](image1)

![Fig. 12. Comparison of selected system eigenvalues with WPP voltage controller.](image2)

![Fig. 13. Mode shape for the generator speed state for three inter-area modes. The presented mode shapes are for case 1 with $P_{\text{WPP}} = 1\,000$ MW and with a WPP voltage controller in service.](image3)

![Fig. 14. Comparison of selected system eigenvalues with WPP voltage controller.](image4)

### TABLE VI

<table>
<thead>
<tr>
<th>Case</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-0.278 \pm j3.15$</td>
<td>$-0.663 \pm j6.26$</td>
<td>$-0.644 \pm j8.83$</td>
</tr>
<tr>
<td>2</td>
<td>$-0.287 \pm j3.25$</td>
<td>$-0.668 \pm j6.27$</td>
<td>$-0.644 \pm j8.83$</td>
</tr>
</tbody>
</table>

### TABLE VII

| State variables | $| p_1 |$ case 1 | $| p_1 |$ case 2 |
|-----------------|-------------|-------------|
| $\delta (G_2)$  | 0.10        | 0.04        |
| $\delta (G_3)$  | $< 10^{-2}$ | $< 10^{-2}$ |
| $\delta (G_4)$  | 0.03        | 0.03        |
| $\delta (G_5)$  | 0.03        | 0.03        |
| $\delta (G_6)$  | 0.08        | 0.07        |
| $\delta (G_7)$  | 0.01        | 0.01        |
| $\delta (\text{WPP})$ | $< 10^{-7}$ | $< 10^{-7}$ |
| $\delta (\text{WPP})$ | $< 10^{-5}$ | $< 10^{-5}$ |
| $\delta (\text{WPP})$ | $< 10^{-5}$ | $< 10^{-5}$ |

### V. Discussion

This paper presents a modal analysis of full-load converter interfaced WTs. Focus of the work is the impact increased wind power penetration has on power system inter-area oscillations. The study is based on a 18 node, 7 generator power system model to which the WPP is connected. The system model represents a large network with a reduced number of nodes and has been developed in collaboration with National Grid to assist in the understanding of power oscillations between major areas of the UK power system. The attached WPP is modeled as an aggregated machine which includes all grid significant components [29]. The WPP is furthermore equipped with a voltage controller that controls the voltage at the interface to the external grid.

To accommodate the production from additional generation units, assuming that load and power transfer to neighboring systems does not increase, the production from the existing units should decrease accordingly to keep the power balance. Two ways this can happen are 1) all units stay connected but with reduced active power output, or 2) a proportion of the existing units are taken out of service to ensure good utilization of the units in service.
Three inter-area modes are monitored as the penetration of wind power increases, and both with and without WPP voltage controller the inter-area modes seem largely unaffected by the increased capacity of the WPP. Comparing the inter-area characteristics in TABLE II, IV, and VI it is noted that the damping of the three inter-area modes is almost constant, while the frequency of oscillation, especially for $\lambda_1$, increases slightly. For inter-area mode $\lambda_1$ the damped frequency of oscillation increases by 4% in case 2 where the synchronous generator, $G_2$, is being displaced by the WPP.

The WPP voltage controller does not significantly change the modal properties of the system. A comparison of the results in section IV-A and IV-B shows a large degree of uniformity, with the trajectories in the complex plane in Fig. 10 and 12 being almost identical.

The degree of interaction of the WPP in the power system oscillations is evaluated with the aid of participation factors. The participation in the system oscillations of the WPP mechanical system are orders of magnitude smaller than those computed for the synchronous machines. This could imply a decoupling between the grid dynamics and the WPP mechanical system by the full-load converter.

VI. CONCLUSION

In this paper a modal analysis is presented where the impact of full-load converter interfaced wind turbines on power system oscillations is evaluated. The analysis is repeated for various wind power penetration levels, two different strategies for accommodating the wind energy, and with and without a wind power plant voltage controller.

The study found that the inter-area modes were largely unaffected by the increased capacity of the wind power plant. The damping of three selected inter-area modes was almost unchanged for the analyzed cases while smaller increases, < 4%, were seen in the damped frequency of oscillation.

Generally, a very small participation from the wind turbines was found in the system oscillatory modes, hence implying that the wind power plant does not interact with these system modes.

APPENDIX A

System Parameters

TABLE VIII

<table>
<thead>
<tr>
<th>Generators MVA</th>
<th>Transformers [%]</th>
<th>Loads [MVAr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$ 3000</td>
<td>$T_1$, $X_L = 16$</td>
<td>$L_3$ 755 + 2220</td>
</tr>
<tr>
<td>$G_2$ 2400</td>
<td>$T_2$, $X_L = 16$</td>
<td>$L_4$ 4280 + j1580</td>
</tr>
<tr>
<td>$G_3$ 1000</td>
<td>$T_3$, $X_L = 16$</td>
<td>$L_5$ 3200 + j954</td>
</tr>
<tr>
<td>$G_4$ 7.300</td>
<td>$T_4$, $X_L = 16$</td>
<td>$L_6$ 6310 + j2030</td>
</tr>
<tr>
<td>$G_5$ 2.900</td>
<td>$T_5$, $X_L = 16$</td>
<td>$L_7$ 2910 + j260</td>
</tr>
<tr>
<td>$G_6$ 5.500</td>
<td>$T_6$, $X_L = 16$</td>
<td>$L_8$ 2500 + j775</td>
</tr>
<tr>
<td>$G_7$ 2.800</td>
<td>$T_7$, $X_L = 16$</td>
<td></td>
</tr>
</tbody>
</table>


Thyge Knudped received his M.Sc.E.E degree from the Technical University of Denmark (DTU) in the spring of 2008 where he specialized in power systems and control theory. Currently, he is employed as research engineer at Siemens Wind Power A/S and is pursuing a PhD degree from DTU.

Vladislav Akhmatov holds M.Sc. (1999) and Ph.D. (2003) degrees from the Technical University of Denmark, Kgs. Lyngby, Denmark. He has been with the Danish power company NESA, now part of DONG Energy, the Danish transmission system operator Energinet.dk, Centre for Electric Technology at the Technical University of Denmark, and at present he is a Senior Engineer and Chief Specialist with the wind turbine manufacturer Siemens Wind Power. His main interests are wind turbine modeling, wind power grid-integration, power system modeling, operation and stability. He has authored and co-authored several papers and books on the topics of interests.

Jørgen N. Nielsen holds M.Sc. (1996) and Ph.D. (2000) degrees from the Technical University of Denmark, Kgs. Lyngby, Denmark. He has a broad and comprehensive knowledge and experience on power system planning, network investigations and power system simulations. Jørgen N. Nielsen has performed and been responsible for a number of network investigations and studies issued the integration of wind power in the power system and been deeply involved into the development of numerical PSS/E simulation models of the fixed- and variable-speed wind turbines.

Kim H. Jensen holds M.Sc. (1999) and Ph.D. (2003) degrees from the Technical University of Denmark, Kgs. Lyngby, Denmark. He has been working in a transmission company (NESA), consultant company (Elsam Engineering) and now a wind turbine company (Siemens Wind Power). In these companies he has worked with transmission system planning, network designs, wind turbine modelling, grid codes studies and harmonic analysis and stability studies. He has also worked as technical specialist on an number wind farm integration projects.

Andrew Dixon holds B.Sc. and Ph.D. degrees in Applied Mathematics (1984-1988) from the University of St Andrews, Scotland and an M.Sc. in Electric Power Systems (2005) from the University of Bath, England. Dr. Dixon has worked for 19 years for the National Grid Company, UK, consisting of: Research & Development (security-constrained optimization of reactive compensation) - 2 years; System Development & Grid Code - 6 years; Operational Planning - 4 years; Asset Management - 2 years; System Technical Performance (dynamics, including transient stability, small-signal stability & sub-synchronous resonance) - 5 years.
Jacob Østergaard is professor in Electric Technology, Head of Centre for Electric Technology (CET) and Head of Section for Electric Power Engineering at the Department of Electrical Engineering, DTU. From 1995 to 2005 he worked as research engineer and area responsible at Research Institute for Danish Electric Utilities (DEFU). Current activities include research within electricity production, transmission, distribution and demand. Prof. Østergaard is presently involved in activities related to an intelligent power system with focus of new electricity and information architectures, system integration of distributed generation and increased flexibility in the power system by use of demand side participation. Prof. Østergaard is project leader of more than 10 research projects and serves in several professional organizations including the EU SmartGrids advisory council.