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Small-Signal Stability Analysis of Full-Load Converter Interfaced Wind Turbines

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

Abstract—Power system stability investigations of wind farms often cover the tasks of low-voltage-fault-ride-through, voltage and reactive power control, and power balancing, but not much attention has yet been paid to the task of small-signal stability. Small-signal stability analysis needs increasing focus since the share of wind power increases substituting power generation from conventional power plants. Here, a study based on modal analysis is presented which investigate the effect of large scale integration of full-load converter interfaced wind turbines on inter-area oscillations in a three generator network. A detailed aggregated wind turbine model is employed which includes all necessary control functions. It is shown that the wind turbines have very low participation in the inter-area power oscillation.

Index Terms—wind turbines, wind farms, power systems, model, small-signal stability, modal analysis

I. INTRODUCTION

THE present and scheduled rapid increase of installed capacity of wind energy conversion systems (WECS) and in particular large wind farms (WF) are changing the role and the impact of wind power on operation of power systems. This development is already noted in the grid codes from some transmission system operators, where large WFs are termed power park modules and must comply with similar requirements to those for other generation units.

One aspect of this is the system ancillary services, which today in many countries are usually provided by conventional units based on synchronous generators. However, as the penetration of wind power increases, production from conventional units is displaced and it may be necessary to secure adequate system ancillary services from WECS. In a number of publications the ability of wind power to provide primary and secondary frequency reserves [1]–[4] are investigated, as well as voltage and reactive power control [5], [6]. In some countries, for instance Denmark, WFs are already applied for ancillary services, e.g. frequency reserve.

Regarding power system stability investigations, considerable attention has been paid to low-voltage-fault-ride-through capabilities of the wind turbines (WT), ie. the ability of the WTs to stay connected during external disturbances in the grid

and provide necessary voltage support [6]–[8]. With increasing penetration of WECS and increasing size of each installed WF new stability considerations arise. A topic of increasing importance is the effect of WFs on power system small-signal stability, including influence on power system oscillations.

In the literature a number of studies analyze the impact of fixed- and variable-speed WTs on power system oscillations [9]–[13]. In [9]–[11] comparisons are presented of the influence on power system oscillations of WFs based on fixed-speed induction generators (FSIGs) and doubly fed induction generators (DFIGs). The references found that FSIG increases the damping of the power oscillations, [9], [11] also find a positive contribution to the damping from the DFIG machine while [10] note that the DFIG does not have any significant effect on the damping. Reference [12] analyzes the influence of the voltage/VAR control mode of a WF based on DFIGs 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 WF in voltage control mode [12] finds 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.

Reference [14] develops a small-signal dynamic model of an aggregated fixed-speed WF using a sensitivity approach based on singular value decomposition. In [15] the same authors extend the work from [14] to include variable-speed WECS, namely DFIG and full-load converter interfaced WTs.

A few publications have investigated the possibility of using variable-speed WFs actively to damp power system oscillations [16]–[18].

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 analysis is based on a three 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 impact on the oscillatory inter-area mode is analyzed by observing the movement of the system eigenvalues in the complex plane, as wind power gradually displaces one of the synchronous generators representing an area of the UK system. Modern variable-speed wind turbines have several operation regimes and to illustrate their impact on system oscillations, the analysis is performed for each operation regime. The eigenvalue analysis, which is by its nature a linear approach, is supplemented with time domain simulations of the non-linear

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system.

Full-load converter interfaced WTs effectively decouple the generator dynamics from the dynamics of the grid, and the WT generators hence cannot contribute to power system oscillations. However, as the WTs and the WFs are controlled to provide ancillary services with voltage- and frequency support, it is likely that the control capability of the WTs and WFs can interact with the system dynamics e.g. other generators in the system. Participation factors are used to identify states, which play a dominant part in the oscillatory modes.

The paper is organized as follows. In section II the basis for the analysis is established with a description of modal analysis, power system oscillations, and the analyzed WECS concept. Section III presents the study case, the case studies performed, and the results from 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 [19]. Power system oscillations and the application of eigenvalue analysis as means of analysis are well described in the literature, e.g. [20], [21].

A. Eigenvalue Analysis

The analysis is based on the non-linear 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

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}\end{aligned}\quad (1)$$

where $\mathbf{x}^{n \times 1}$ is the state vector, $\mathbf{u}^{r \times 1}$ the input vector, $\mathbf{y}^{m \times 1}$ the output vector, $\mathbf{A}^{n \times n}$ is the system state matrix, $\mathbf{B}^{n \times r}$ the input matrix, $\mathbf{C}^{m \times n}$ the output matrix, and $\mathbf{D}^{m \times r}$ 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 \mathbf{A} , i.e. decouple the system dynamics.

$$\mathbf{A}\boldsymbol{\phi}_i = \lambda_i\boldsymbol{\phi}_i, \quad \text{for } i = 1, 2, \dots, n \quad (2)$$

where the eigenvalue, λ_i , is found as the solution of

$$\det(\mathbf{A} - \lambda_i\mathbf{I}) = 0 \quad (3)$$

and where \mathbf{I} is the identity matrix and $\boldsymbol{\phi}_i^{n \times 1}$ 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

$$\boldsymbol{\psi}_i^T \mathbf{A} = \lambda_i \boldsymbol{\psi}_i^T, \quad \text{for } i = 1, 2, \dots, n \quad (4)$$

where $\boldsymbol{\psi}_i^{1 \times n}$ 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

$$\boldsymbol{\Phi} = [\boldsymbol{\phi}_1 \ \boldsymbol{\phi}_2 \ \dots \ \boldsymbol{\phi}_n] \quad \boldsymbol{\Psi} = [\boldsymbol{\psi}_1^T \ \boldsymbol{\psi}_2^T \ \dots \ \boldsymbol{\psi}_n^T]^T \quad (5)$$

Further, for power system studies the eigenvector matrices are usually scaled to satisfy $\boldsymbol{\Psi}\boldsymbol{\Phi} = \mathbf{I}$.

The right eigenvector, $\boldsymbol{\phi}_i$, describes how the activity of the i th mode is distributed on the n state variables, while the left eigenvector, $\boldsymbol{\psi}_i$, weighs the contribution of the n state variables on the i th mode. The entrywise product of $\boldsymbol{\phi}_i$ and $\boldsymbol{\psi}_i^T$ is thus a measure of the importance of the states within the individual modes and is referred to as the participation factors

$$\mathbf{p}_i = [\boldsymbol{\phi}_{1i}\boldsymbol{\psi}_{i1} \ \boldsymbol{\phi}_{2i}\boldsymbol{\psi}_{i2} \ \dots \ \boldsymbol{\phi}_{ni}\boldsymbol{\psi}_{in}]^T, \quad (6)$$

or in compact notation

$$\mathbf{P} = \boldsymbol{\Phi} \otimes \boldsymbol{\Psi}^T \quad (7)$$

where \otimes denotes the entrywise product of two equal sized matrices.

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 $\lambda_i = a \pm jb$, the natural frequency, ω_n , the damped frequency, ω_d , and the damping ratio, ζ , are defined as

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

From classical control theory of continuous time systems, it is given that mode λ_i is asymptotically stable only if $a < 0$.

It should be remembered that power systems in general are non-linear 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. 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 groups 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 $f \in [0.1 \ 0.3]$ 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. Characteristics of Case Network

The study is based on an eight node network which consists of three synchronous generators, two loads, and an aggregated WF; the single-line diagram of the network is depicted in Fig. 1 and it represents a large network that has been reduced to a small number of nodes. A similar network is applied in [9] for the assessment of ‘‘Influence of Windfarms on Power System Dynamic and Transient Stability’’. Although the network is very simple it does assist in the understanding of power oscillations between major areas of the UK power system. The parameters for the synchronous generators, the network, and for load and generation are found as appendix A. The system is tuned for a light load situation, where the loads and the loading of each generator implies a southbound active power flow of around 2 200 MW.

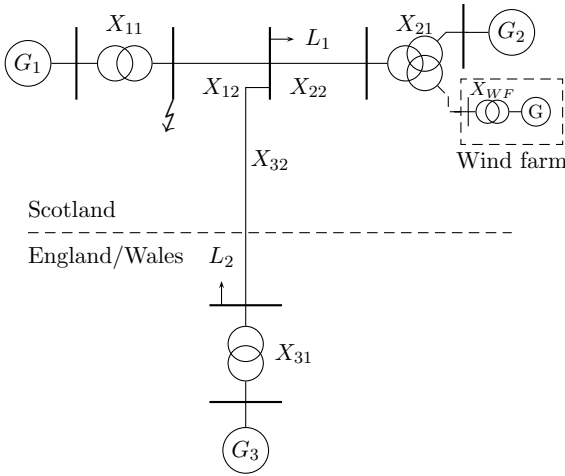


Fig. 1. Single-line diagram of the analyzed case network.

The dominant dynamic behavior of the network is an inter-area mode between G_3 and G_1+G_2 the boundary of which is marked in Fig. 1 by a dashed line. The inter-area mode is initially unstable but is stabilized with a power system stabilizer (PSS) connected at G_1 . The mode-shape for the inter-area mode is plotted in Fig. 2. The dominant characteristic of the system is summarized in Table I and the participation factors in Table II.

In Fig. 3 a time domain simulation is presented where a three-phase short-circuit of suitable duration is applied, and then efficiently cleared, at the HV bus of the machine transformer of G_1 . The ordinate is scaled to enhance readability of the power oscillations. Immediately after the fast transients have decayed G_1 is seen to oscillate against G_2 for 1-2 cycles. This oscillation is followed by the dominant 0.5 Hz inter-area oscillation, noticed in both the inter-area active power flow and in the active power production from the generators with a 180° displacement between G_1+G_2 and G_3 .

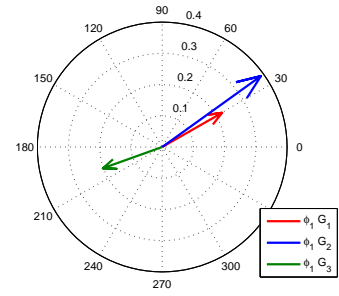


Fig. 2. Mode-shape for generator rotor angle states for the inter-area mode with PSS at G_1 enabled.

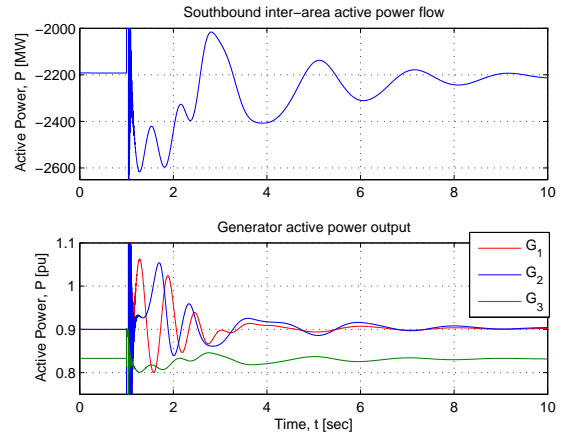


Fig. 3. Generator active power production and inter-area active power flow after three-phase short-circuit at HV terminals of transformer X_{11} .

TABLE I
CHARACTERISTIC FOR INTER-AREA MODE

λ	ω_d	ζ
[-]	[Hz]	[-]
$-0.626 \pm j3.18$	0.503	0.194

TABLE II
NORMALIZED ROTOR ANGLE PARTICIPATION FACTORS FOR INTER-AREA MODE

State variable	$ p_{ij} $
$\delta (G_1)$	0.34
$\delta (G_2)$	0.17
$\delta (G_3)$	0.30

Now, the WF is connected through a three-winding transformer at G_2 with equivalent impedances for G_2 and the WF. This approach is chosen since it allows connection of the WF without altering the topology of the network.

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. 4 and further described in [22].

- *Aerodynamic model.* A variable wind speed aerodynamic model which includes power coefficient with pitch angle and tip-speed ratio.

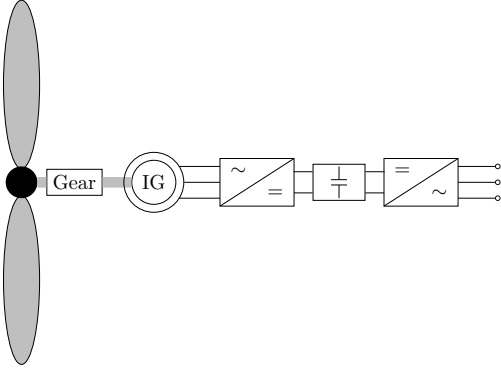


Fig. 4. Wind turbine concept used in the analysis: full-load converter interfaced WT.

- *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 system and the WF, i.e. all dynamics internally in the WF as well as any mutual interaction between the WTs are neglected. The WTs are operated in voltage control mode, regulating for 1 p.u. at the WT terminal.

C. 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 X.

Generator G_1 and G_2 are equipped with a static excitation system with AVR control and is implemented as an IEEE type ST1A excitation system. For generator G_3 an IEEE type AC4A excitation system is employed. The system is stabilized with a PSS connected at G_1 , here an IEEE PSS 4B type model is implemented.

Generic models are employed for the steam turbines and the associated governors.

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 mode.

Three cases with a varying penetration of wind power are investigated and compared to the base case with only synchronous generation

- 1) P_{setp} 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
- 3) As case 2) but with the WF modeled as a constant impedance model with power factor 1.

In all cases and for all wind power penetration levels, active power production is shifted between only G_2 and the WF 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 WF. While in case 2, the wind power displaces conventional units and the MVA rating of G_2 is reduced accordingly. Case 3 is included to challenge the hypothesis of complete decoupling by the converter between WT generator side and the grid. The model in case 3 does not represent the complex dynamics of the WF, however, it does illustrate the impact of the alternate power injection point. In each case the size of the WF is varied linearly from 36 to 1 000 MW in 10 steps.

To identify which effects the WF operating mode may have on the eigenvalue movement, the study is repeated for the WT operating at (a) rated power output, (b) in power tracking, and in (c) speed tracking; the results are presented in sections IV-A, IV-B, and IV-C, respectively. For (b) and (c) case 3 is neglected as no control dynamics are included in the constant impedance model.

A list of dominant eigenvalues for the system is given in Table III; the inter-area oscillation is identified as λ_1 .

TABLE III
QUALITATIVE DESCRIPTION OF DOMINANT EIGENVALUES

λ_1	Inter-area mode, G_1, G_2 against G_3
λ_2	Primarily mech. syst. of G_1, G_2 and PSS at G_1
λ_3	Excitation mode, G_1, G_2
λ_4	Voltage controller common mode, G_1, G_2, WF
λ_5	Voltage controller common mode, G_1, G_2, WF

A. WF Operated at Rated Power Output

A comparison of the inter-area mode in the last iteration with 1 000 MW of wind power is given in Table IV. In all cases the frequency of the inter-area oscillation is slightly decreased as the penetration of wind power increases. When the rating of G_2 is reduced the inter-area mode damping is increased, while the damping is reduced in case 1 where the MVA rating is constant and the set-point reduced.

TABLE IV
CHARACTERISTICS FOR INTER-AREA MODE WITH 1 000 MW OF WIND POWER

	λ [-]	ω_d [Hz]	ζ [-]
Case 1	$-0.519 \pm j2.97$	0.473	0.172
Case 2	$-0.792 \pm j3.05$	0.485	0.252
Case 3	$-0.861 \pm j3.04$	0.483	0.273

An overview of the complex plane with dominant system eigenvalues is shown in Fig. 5 for case 2, where the MVA

rating of G_2 is reduced as the WF output increases. A comparison of dominant eigenvalues is given in Fig. 6 where the movement of the eigenvalues in Table III for each case are plotted together.

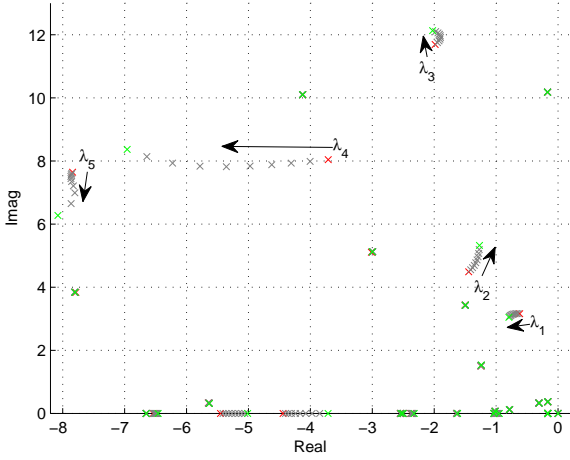


Fig. 5. Movement of system eigenvalues with increasing penetration of wind power when the MVA rating G_2 is reduced accordingly. Red: WF size of 36 MW. Green: WF size of 1000 MW.

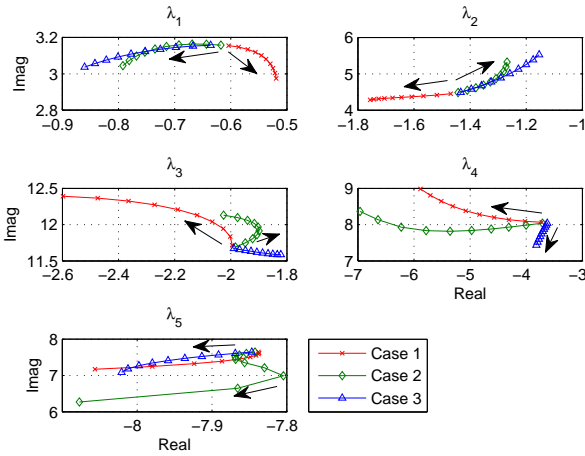


Fig. 6. Comparison of the three cases with the WF operating at rated power output.

Table V shows a comparison of selected participation factors for the inter-area oscillation, λ_1 , for the three cases. Participation factors for generator rotor angles are shown for the synchronous generators, while mechanical angle states for generator, rotor, and shaft are shown for the WF. Furthermore, the largest participation factor for the WF states is given; in both cases this corresponds to the reactive current controller in the WTs. In case 3, a simple constant impedance model represents the WF and no dynamic control are included in the model, hence the WF states are non-existing.

The WF participation in the inter-area oscillation is very small with participation factors a hundred times smaller than those of the synchronous generators, cf. Table V. This charac-

teristic is noticed for both case 1 and 2 and thus independent of the size of G_2 . Consider the movement of the eigenvalues, λ_1 - λ_2 , in Fig. 6, it is interesting to notice the similarity between case 2 and 3; this could imply that the dynamics of the WF mechanical system do not interact with those of the synchronous generators. However, one should be careful when comparing case 2 and 3 since the complex dynamics of the WF are not represented with the simple impedance model in case 3. The similarities in the eigenvalue trajectories disappear when the voltage controller modes are compared, λ_3 - λ_5 . In fact, in case 3 after around 700 MW an unstable mode appears in which dq -axis fluxes of G_1 and G_2 are the main participants (not shown in Fig. 6).

TABLE V
COMPARISON OF SELECTED PARTICIPATION FACTORS FOR THE INTER-AREA MODE, λ_1 , FOR THE THREE CASES. FOR THE WF PARTICIPATION FACTORS ARE SHOWN FOR MECHANICAL GENERATOR-, ROTOR- AND SHAFT-ANGLE STATES, AND THE MAXIMUM PARTICIPATION OVER ALL WF STATES.

State variables	$ p_1 $ case 1	$ p_1 $ case 2	$ p_1 $ case 3
$\delta(G_1)$	0.25	0.36	0.35
$\delta(G_2)$	0.16	0.08	0.06
$\delta(G_3)$	0.27	0.26	0.25
δ_g (WF)	$< 10^{-4}$	$< 10^{-4}$	-
δ_r (WF)	$< 10^{-6}$	$< 10^{-5}$	-
δ_s (WF)	$< 10^{-4}$	$< 10^{-4}$	-
$\max(p_1)$ (WF)	0.01	0.02	-

The mode-shapes of the inter-area mode with maximum penetration of wind power are plotted in Fig. 7 and these should be compared to the mode-shape in the base case without wind power in Fig. 2. For case 2 and 3, where the MVA rating of G_2 is reduced, it is noted that the inter-area characteristic with 180° separation between the vectors is less pronounced than in the base case or in case 1. This behavior is also noticed from the participation factors in Table V with reduced participation of G_2 in the mode.

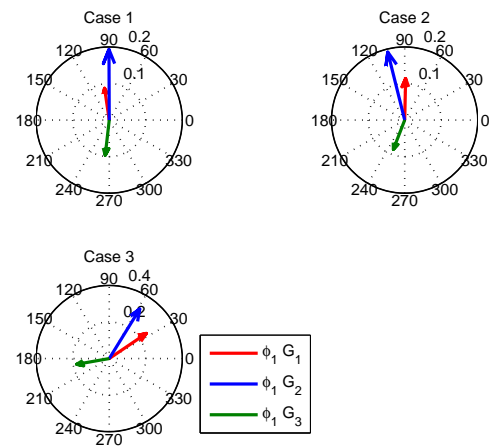


Fig. 7. Comparison of the three cases with the WF operating at rated power output. The mode-shape is computed for the last iteration with 1000 MW of wind power.

B. WF operated at Power Tracking

As the available amount of wind changes, variable-speed WTs change the operating mode to extract maximum power from the wind. In power tracking mode, the mechanical rotational speed is kept constant, and the blade pitch angle is fixed for maximum power extraction. For this study the WF active power output is 0.69 p.u. on the WF base.

Table VI provides a comparison of the inter-area mode with an installed WF capacity of 1000 MW. The Table reveals that the oscillating frequency is reduced with more than 20 %, while the damping is increased by app. 10 % and 35 % for case 1 and 2, respectively.

TABLE VI
CHARACTERISTICS FOR INTER-AREA MODE WITH 1000 MW OF WIND POWER

	λ [-]	ω_d [Hz]	ζ [-]
Case 1	$-0.540 \pm j2.44$	0.388	0.217
Case 2	$-0.686 \pm j2.47$	0.393	0.264

A comparison of the dominant eigenvalues are presented in Fig. 8.

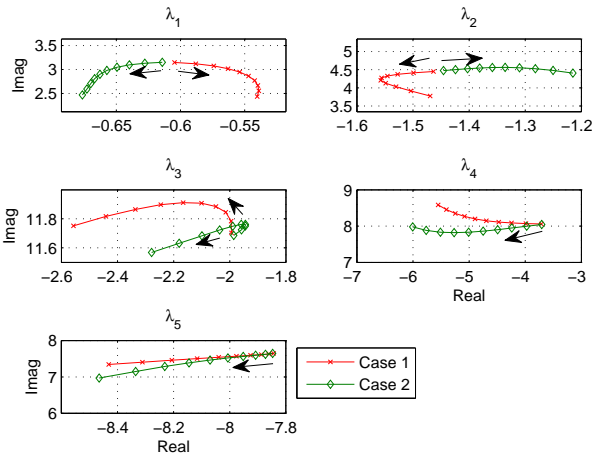


Fig. 8. Comparison of the two cases with the WF operating at power tracking.

The participation factors for the generator rotor angles as well as the WF mechanical states are shown in Table VII. Again, the very low participation of the WF in the inter-area oscillation is noted. The largest WF participation is found in the reactive current controller.

C. WF operated at Speed Tracking

At lower wind speeds it proves advantageous to reduce the tip-speed ratio from rated speed in order to maximize the power extraction coefficient. This operating mode is applied between cut-in wind speed and the rated rotational speed of the machine. In this study an operating point is selected with an active power output of 0.31 p.u. on WF base.

The modal characteristics for the inter-area mode with an installed WF capacity of 1000 MW are summarized in Table VIII. For both cases the damping has increased as

TABLE VII
COMPARISON OF SELECTED PARTICIPATION FACTORS FOR THE INTER-AREA MODE, λ_1 , FOR CASE 1 AND 2. FOR THE WF PARTICIPATION FACTORS ARE SHOWN FOR MECHANICAL GENERATOR-, ROTOR- AND SHAFT-ANGLE STATES, AND THE MAXIMUM PARTICIPATION OVER ALL WF STATES.

State variables	$ p_1 $ case 1	$ p_1 $ case 2
$\delta (G_1)$	0.22	0.28
$\delta (G_2)$	0.13	0.09
$\delta (G_3)$	0.27	0.27
δ_g (WF)	$< 10^{-4}$	$< 10^{-4}$
δ_r (WF)	$< 10^{-5}$	$< 10^{-5}$
δ_s (WF)	$< 10^{-4}$	$< 10^{-4}$
$\max(p_1)$ (WF)	0.01	0.01

compared to the no-wind setup and the frequency of the inter-area oscillation reduces.

TABLE VIII
CHARACTERISTICS FOR INTER-AREA MODE WITH 1000 MW OF WIND POWER

	λ [-]	ω_d [Hz]	ζ [-]
Case 1	$-0.614 \pm j2.59$	0.412	0.231
Case 2	$-0.697 \pm j2.59$	0.423	0.260

Fig. 9 provides a comparison of the dominant eigenvalues. Note how the predominant movement in case 1 of the inter-area mode, λ_1 , is to reduce the frequency of the oscillation.

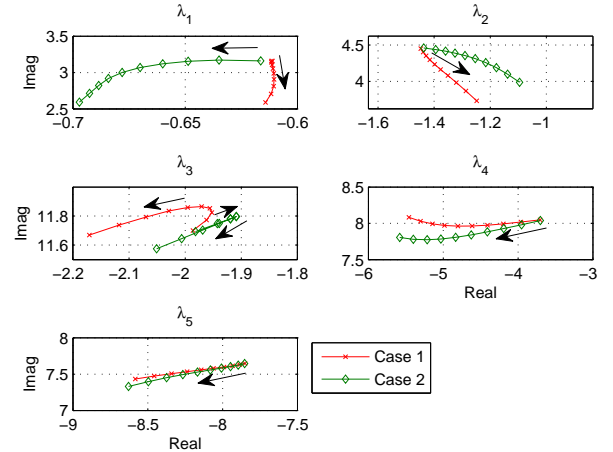


Fig. 9. Comparison of the two cases with the WF operating at speed tracking.

The participation factors in Table IX show similar results as presented in section IV-A and IV-B.

V. DISCUSSION

In this paper a modal analysis of full-load converter interfaced WTs is presented. The work focuses on the impact of increased wind power penetration on inter-area oscillations. To this end, a three generator network is employed which is designed to illustrate some overall dynamics between major areas of the UK power system. The WTs are modeled as an aggregated machine comprising all the grid significant components [22].

TABLE IX

COMPARISON OF SELECTED PARTICIPATION FACTORS FOR THE INTER-AREA MODE, λ_1 , FOR CASE 1 AND 2. FOR THE WF PARTICIPATION FACTORS ARE SHOWN FOR MECHANICAL GENERATOR-, ROTOR- AND SHAFT-ANGLE STATES, AND THE MAXIMUM PARTICIPATION OVER ALL WF STATES.

State variables	$ p_1 $ case 1	$ p_1 $ case 2
$\delta (G_1)$	0.28	0.32
$\delta (G_2)$	0.17	0.13
$\delta (G_3)$	0.28	0.28
δ_g (WF)	$< 10^{-6}$	$< 10^{-6}$
δ_r (WF)	$< 10^{-5}$	$< 10^{-5}$
δ_s (WF)	$< 10^{-5}$	$< 10^{-5}$
$\max_x(p_1)$ (WF)	0.01	0.02

The effect of increased penetration of wind power is analyzed through two cases. In one case the WF does not affect the number of on-line conventional units but only the active power set-point for these units; where in the second case, conventional units are disconnected to accommodate the wind power. Modern variable-speed WTs have multiple modes of operation and to analyze which effect these operation regimes may have, the two cases are repeated for rated power operation, speed tracking, and for power tracking.

In addition to the two aforementioned cases, a third is studied where the WF is merely represented as a negative impedance. For the modes dominated by synchronous generator rotor angle states, the response is somewhat similar to that of the detailed model. However, the movement is quite different for other dominant eigenvalues, such as those associated with the voltage controllers. Furthermore, an unstable mode appears after about 700 MW of installed capacity, which is not seen when the detailed WF model is employed. It is important to realize that the negative impedance model does not represent the full-load converter interfaced WT and it illustrates the importance of using models of sufficient accuracy.

The interaction of the WF with the power system oscillation is evaluated using participation factors and for all the studied cases the pattern is the same, with very low participation from the WF in the oscillatory system mode. These results indicate that the WT mechanical system is decoupled from the dynamics of the grid by the full-load converter.

As the installed capacity in the WF increases, a common trend in the results is that the frequency of the inter-area mode decreases; usually a sign of a reduction of the generator synchronizing torque [20]; as given by

$$\omega_n = \sqrt{K_S \frac{\omega_0}{2H}} \quad (8)$$

where K_S is the synchronizing torque coefficient. The effect is most pronounced when the WF is operating in speed or power tracking, which could be explained by the higher reactive power control capability the WT has in these operating modes. Increased capacity of wind power generally had a favorable effect on the inter-area mode damping. Further studies will look into how much of these effects that can be ascribed to the WT and how much is an indirect effect, i.e. changes in the operation of the remaining system due to the power injection from a unit not based on a synchronous generator.

Furthermore, it should be mentioned that the eigenvalue movement in the modal analysis is influenced by several parameters such as network impedance, exciter gain, PSS design, operating point etc.; to mention just a few parameters, whereas this study has only covered a part of the parameter space.

VI. CONCLUSION

This paper presents a modal analysis of a full-load converter interfaced WT to evaluate its influence on inter-area oscillations. The analysis is repeated for various wind power penetration levels and for different WT operating modes.

With increased installed capacity of wind power, the study found that the general trend for the inter-area mode is increased damping and a decreased frequency of oscillation.

The study found that the WT systems have a very low participation in the inter-area oscillation of the system, and hence, that the WT does not interact with this mode of oscillation. These initial results could indicate that the full-load converter does in fact decouple the network dynamics from the WT generator dynamics, however, this requires more investigations.

APPENDIX A SYSTEM PARAMETERS

TABLE X
GENERATOR RATINGS AND LOAD CHARACTERISTICS

Generators [MVA]		Loads [MVA]	
G_1	2 800	L_1	2 500 + j 830
G_2	2 400	L_2	20 000 + j 6 600
G_3	21 000		

TABLE XI
MACHINE PARAMETERS FOR ALL SYNCHRONOUS GENERATORS.

$T'_{d\phi}$	6.0857 s	$T'_{q\phi}$	1.653 s
$T'_{d\omega}$	0.0526 s	$T'_{q\omega}$	0.3538 s
H	3.84 s	D	0 s
X_d	2.13 pu	X_q	2.07 pu
X'_d	0.308 pu	X'_q	0.906 pu
X''_d	0.234 pu	X''_q	0.234 pu
X'_l	0.190 pu		
Sat. (1.0)	0.150 pu	Sat. (1.2)	0.7025 pu

TABLE XII
LINE REACTANCES ARE ON A 100 MVA BASE WHILE TRANSFORMER REACTANCES ARE ON RATED POWER BASE FOR EACH TRANSFORMER.

X_{11}	2.1 %	X_{12}	0.25 %
X_{21}	2.1 %	X_{22}	2.00 %
X_{31}	2.1 %	X_{32}	2.83 %

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