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Book of Abstracts

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Magdeburg 2008

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Institut of Electric Power Systems
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Introduction

The importance of wind generation has rapidly increased in the past decade, and according to the national plans of most EU-countries will continue to increase especially due to the planned offshore wind parks. As a result, new challenges in various fields of research, such as aerodynamics, structural issues, grid integration, and control aspects have to be addressed.

To face up to these challenges the European Academy of Wind Energy (EAWE) was founded in 2003. The goal of this initiative is to integrate the activities of the highest level academic and research institutes in Europe that are working on wind energy issues, whereby particular attention is paid to spreading excellence through joint education and training activities. One such activity is workshops for PhD students that are regularly organized at both the national and international level.

The fourth international PhD Seminar on Wind Energy in Europe, held at the Otto-von-Guericke-University in Magdeburg, Germany, was attended by over 100 participants including PhD students, supervisors and industry representatives. It was organized under the patronage of Dr. Reiner Haseloff, the Minister for Economic Affairs of Saxony-Anhalt.

This book of abstracts contains the contributions of each participating PhD student, which were presented during the seminar according to the new workshop structure in both an oral as well as a poster session. The role of a short oral presentation was to initiate in-depth discussions during the poster session.

The local organizing committee would like to thank the seminar sponsors and partners for their financial as well as organizational support.

Magdeburg, September 2008 Prof. Dr. Zbigniew A. Styczynski

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SESSION 1
SIMULATION AND MODELLING
- PART I

Wednesday, 01.10.2008

10:00 – 12:30

Building 22A / Room 021 (H2)

Supervisor:

Prof. A. Orths, Energinet.dk

Chairman:

C. Heyde, Otto-von-Guericke University Magdeburg

Wind Turbine Reliability Modelling

H.Arabian[1), P.J.Tavner[2)]

[1)] Sharif University, Iran, [2)] Durham University, UK

ABSTRACT

This paper proposes a reliability model for the wind turbine systems. The model is derived considering the failure of main subassemblies and their parameters are calculated. The method used is Markov modelling, and it is assumed that the wind turbine system and its main subassemblies are in their useful life period. At first the wind turbine is subdivided into appropriate number of main assemblies, due to data availability. A reliability model is derived for each assembly and wind turbine reliability model could be built by aggregation of these reliability models. Alternative configurations could be compared and reliability and availability index for them could be forecasted.

KEYWORDS

Wind Turbine, Reliability Model

1 INTRODUCTION

Wind power is the fastest growing renewable energy resource, which can also be considered as Distributed Generation (DG). Widespread utilization of wind power imposes considerable effects on the planning and operation of the power system. Reliability evaluation and enhancement is an important factor in modern power system planning and operation. Consequently, reliability assessment of wind turbines is of great importance and will receive more attention in the future due to the increase in wind turbine utilization.

Also due to the competitive environment of the power market, industry prefers the most productive and economic configurations of wind turbines. However, a long-term cost-analysis, including operation and maintenance as well as the first investment costs, would result in a better choice of wind turbine configuration. This is only possible with a comprehensive reliability analysis of the different configurations.

The reliability of wind turbines as a part of a large power system are assessed in many references [1-3], but there have been few studies of wind turbine reliability model as an isolated system rather than a part in a large power system [4]. This paper sets out to fill this gap, paying particular attention to the electrical subassemblies of wind turbine systems.

The most important challenge in this work is the gathering of accurate wind turbine reliability data. This is important because a reliability model can only provide correct conclusions if

h.h.arabian@durham.ac.uk

accurate data are used. This has been achieved in this work by close cooperation with the operation and maintenance team of a wind farm over a significant period [5], guaranteeing the accuracy of the reliability data provided. The next challenge in the work has been the use of Markov modelling for wind turbine subassembly reliability studies, which has not been done before.

The paper is arranged as follows:

In section 2 the reliability model for three types of wind turbine is derived.

Section 3 uses the reliability model derived in section 2 and field data to compare the availability index of selected wind turbine configurations.

Section 4 presents the conclusions.

2 WIND TURBINE RELIABILITY MODEL

2.1 Selected Configurations

The geared wind turbine systems with induction generators, which have been shown to be the most common configurations (more than 55%), used for large wind turbines are selected for this study. More accurately one fixed-speed and two variable-speed wind turbine configurations with induction generators are compared in this paper.

For the fixed-speed wind turbine system, the induction generator is directly connected to the electrical grid, system A in Figure 1. The first type of variable-speed wind turbine considered is a system equipped with a fully rated converter connected to the stator of an induction generator as illustrated in Figure 1 and referred to as System B. The second type of variable-speed wind turbine, using the Doubly-Fed Induction Generator (DFIG) is illustrated in Figure 1 and is referred to as System C.

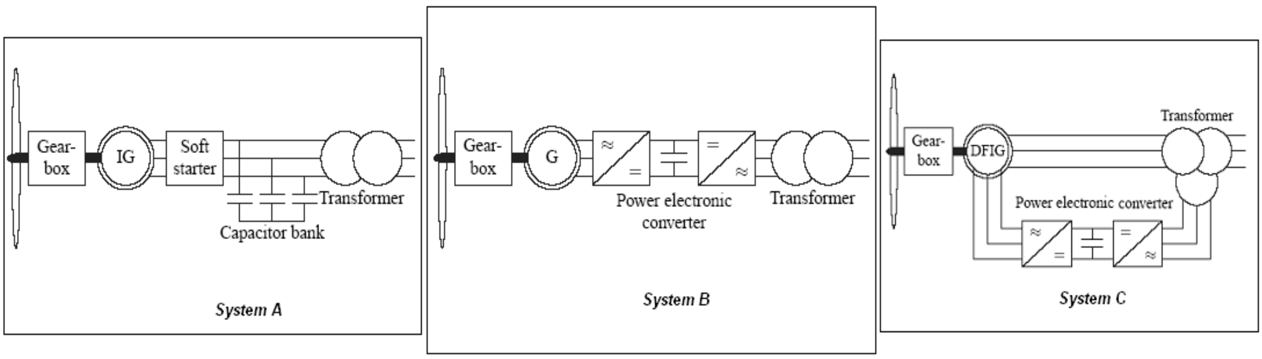

Figure 1: Wind turbine configurations

2.2 Reliability model

According to reliability theory [5] failure and repair rate can be defined respectively as:

λ=Number of failures in a given period of time divided by total period of time the component was operated.

μ=Number of repairs in a given period of time divided by total period of time the component was being repaired.

The useful life period assumption for equipment allows the definition of these transition rates as the reciprocal of average duration of operation and repair

$$\lambda = \frac{1}{MTTF} \quad (1)$$

$$\mu = \frac{1}{MTTR} \quad (2)$$

where MTTF represents Mean Time To Failure and MTTR stands for Mean Time To Repair. Recording the periods of wind turbine operation and repair and taking the average of up-time and down-time gives numerical values for MTTF and MTTR. The same procedure could be conducted for each subassembly to calculate the corresponding failure and repair rates in the time period of the system reliability study.

As the first step only the electrical subassemblies are considered here, but the procedure is the same for inclusion of other subassemblies in wind turbine reliability model. The key point is that by subdivision of each subassembly in its part the appropriate Markov model is derived for it and then using frequency balance method [5], this model is simplified in a simple two-state model of “Up” and “Down” with equivalent failure and repair transition rates.

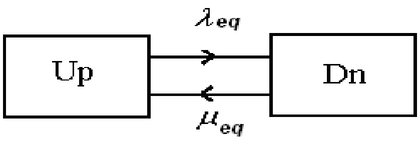

Figure 2: Simple two-state Markov model

Using this approach and considering only electrical parts, generator and converter, and taking into account the interfacing system between generator and converter in system C as “Brush”, the reliability model for these three systems could be derived. These models is shown in Figure 3, in which “IG” stands for induction generator, “Con” shows converter and “Br” is used for brushes.

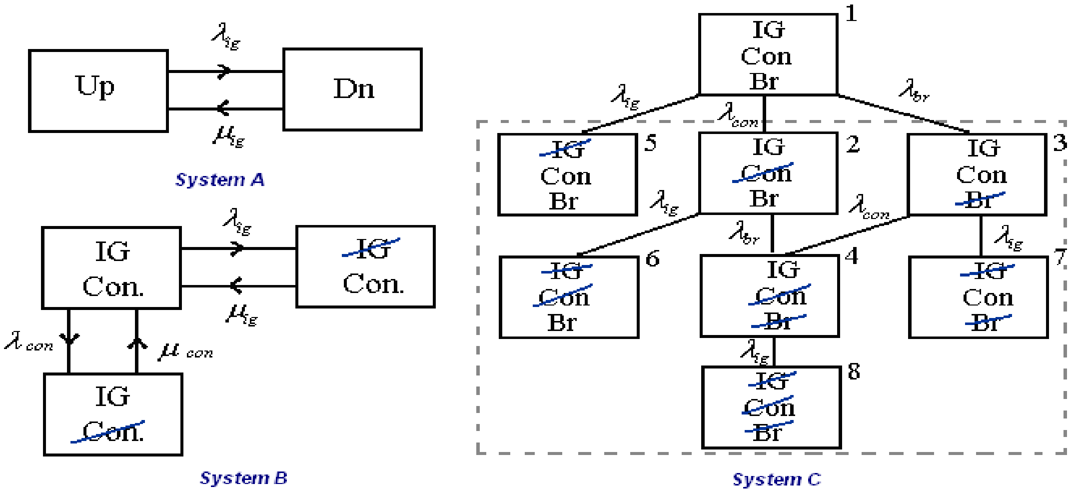

Figure 3: Three wind turbine systems Markov model

It is evident that in system B and C, as shown in Figure 3, the wind turbine is in its "Up" state when all assemblies are in operation. The malfunction of each subassembly is shown by a cross mark on it in Figure 3.

Using frequency balance method [5], the parameters of these models could be derived.

3 NUMERICAL RESULTS

3.1 Field data

The reliability data relates to the subassemblies introduced in Section 2 are tabulated in Table 1. These field reliability data correspond to turbines installed in a wind farm in Iran [6], and may be different to similar generators in other industrial plants. Due to the stresses of wind speed variations, the failure rates of induction generators in wind turbine systems are higher and repair times longer because of the location of the generator in nacelle.

Table 1: Wind Turbine Subassembly Reliability Data

Subassembly	MTTF (Years)	Failure rate(f/year)	MTTR (Days)	Repair rate(rep/year)
Stator	50.0	0.02	10	36.5
Rotor	50.0	0.02	10	36.5
Bearing	12.5	0.08	6	60
Machine-side Inverter	0.8	1.20	5	73
Grid-side Inverter	0.8	1.20	5	73
Control Unit	100.0	0.01	2 hours	4380
DC Link	25.0	0.04	5	73
Brush Gear	10.0	0.10	0.5	730

3.2 Wind turbine comparison

Availability is defined as the probability *to find* a repairable system in its “Up” state in comparison to reliability which is defined as the probability that a system (mission-orientated) *to be* in its “Up” state. Thereafter availability depends not only on inherent reliability of a system but also to repair and maintenance conditions of it.

The steady state probability of system residence in its “Up” state in Markov model is the same as system availability [5].

Using reliability models in section 2 and field data in table 1, the availability for these wind turbine configurations are calculated and compared in table 2.

Table 2: Wind Turbine Availability comparison

Wind turbine system	Availability,%
System A	99.8
System B	96.5
System C	97.0

4 CONCLUSIONS

This paper proposes a reliability model for the electrical subassemblies of geared wind turbine systems with induction generators. The model is derived from considering the failure rates of the main electrical subassemblies, the generator, the power electronic converter and the interface system between the rotor winding and the converter. Using this model and reliability field data, a comparison between three selected configurations of wind turbine was performed. As system A has the simplest configuration its availability is better than the others, but here only the electrical parts was assumed.

BIBLIOGRAPHY

[1] Gavanidou, E.S.; Bakirtzis, A.G.; Dokopoulos, P.S. A probabilistic method for the evaluation of the performance of wind-diesel energy systems; IEEE Transactions on Energy Conversion, Volume 7, Issue 3, Sept. 1992 Page(s):418 – 425

[2] Billinton, R.; Chowdhury, A.A.,Incorporation of wind energy conversion systems in conventional generating capacity adequacy assessment; IEE Proceedings Generation, Transmission and Distribution , Part C Volume 139, Issue 1, Jan. 1992 P.47 – 56

[3] Billinton, R.; Hua Chen, Assessment of risk-based capacity benefit factors associated with wind energy conversion systems; IEEE Transactions on Power Systems, Volume 13, Issue 3, Aug. 1998 Page(s): 1191 – 1196.

[4] Castro Sayas, F.; Allan, R.N.; Generation availability assessment of wind farms, IEE Proceedings Generation, Transmission and Distribution, Part C, Volume 143, Issue 5, Sept. 1996 Page(s): 507 – 518

[5] Billinton,R.; R. N. Allan, ”Reliability Evaluation of Engineering Systems” 2nd Edition, Plenum Press, 1996.

[6] Manjil wind farm, Manjil, Iran.

Inflow Noise, modelling and validation

Brian Riget Broe[1], Jakob Mann[1]

[1] Risø DTU National Laboratory for Sustainable Energy, Denmark

ABSTRACT

The present semi-empirical model for Inflow Noise is believed to overestimate the Inflow Noise and is a subject for improvements.
An aero-dynamical model has been implemented into the acoustical part of the Inflow Noise model. The resulting model is tested against wind tunnel data.

KEYWORDS

Aero acoustics, aerodynamics, unsteady aerodynamics, noise

1 INTRODUCTION, MODELS, AND DATA FOR TESTING MODELS

Noise from wind turbines can be of mechanical or aero dynamical origin. The mechanical noise is an engineering problem and can be reduced and/or be removed by engineering means. Aero dynamical noise (aero acoustics) is due to the flow around the aerofoils and cannot be totally removed. The design of the aerofoil influences the noise of aero dynamical origin. It can be split into several sources, see Figure 1. The dominant source is the Inflow Noise, which is due to pressure fluctuations at the wing caused by atmospheric turbulence. It is generally believed, that Inflow Noise is not the dominant source in reality thus the model for Inflow Noise is subject for improvements and/or validation against data.
The model of Inflow Noise is based on [2]. This model needs as input a model for atmospheric turbulence and a model for the aero dynamical response at the aerofoil. In the present work the aero dynamical models of [3] and [4] are implemented into [2]. Figure 2 and 3 show the lift response for the models of [3] and [4] and a sinusoidal gust impinging an

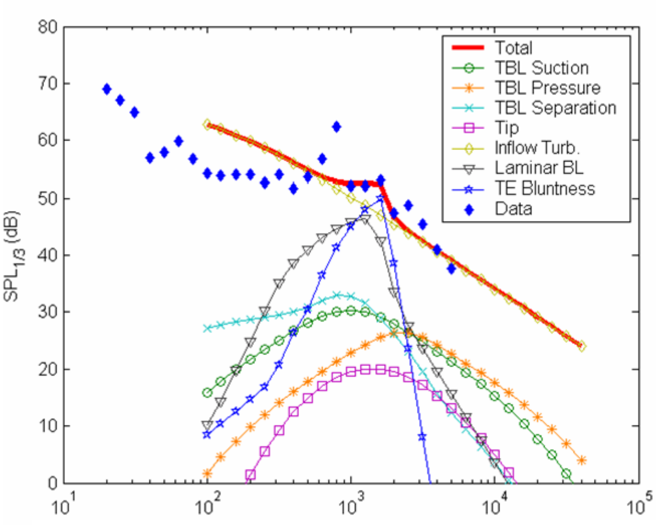

Figure 1. Sound pressure level (SPL) of semi-empirical models of aero dynamical noise at different frequencies. From [1].

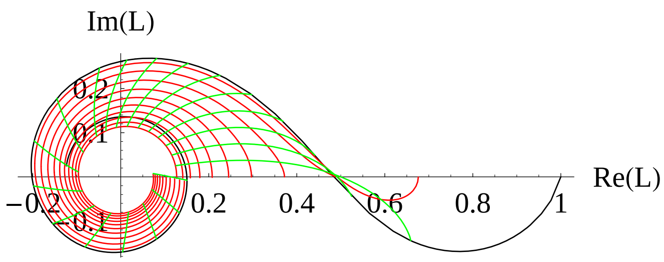

Figure 2. The normalized lift as a function of the 2-dimensional wave number. Red lines are when κ is varied and ν is held constant for different ν (see fig.3.). The Green lines show the lift when κ is held constant and ν is varied for different κ (see fig.3.). Black line is also the one-dimensional model by [3] (ν = 0).

brian.broe@risoe.dk

aerofoil, respectively. Note that the absolute value of the lift response |L| in Figure 2 is the distance from the origin of the plot to a point on, say, the black line. The argument of L is the corresponding phase of the lift at the midpoint of the aerofoil relative to the gust. It is seen that high wave numbers do not give high amplitudes of fluctuating lift. Furthermore gusts with a wave number in the span wise direction do not contribute much to the fluctuating lift.

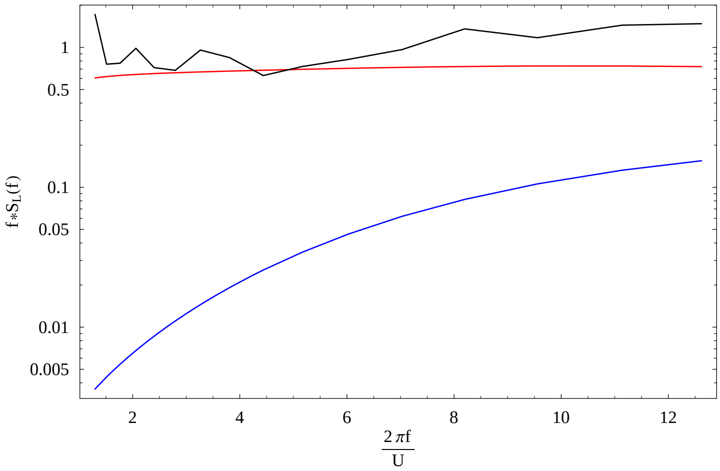

Figure 4. Comparison of data (black) against the models from [3] (red) and [4] (blue).

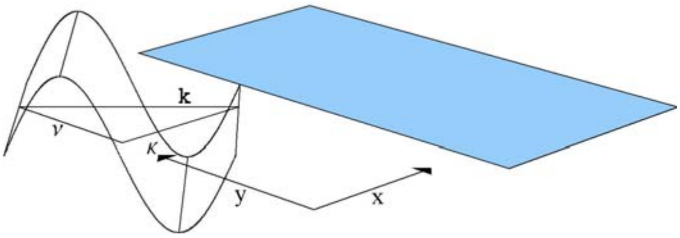

Figure 3. A sinusoidal gust impinging to a semi-infinite flat plate. **k** is the wave vector which is in the plane of the flat plate. The wave vector has the component κ in the x-direction and ν in the y-direction. The wave front hits the edge of the plate in an angle. For the 1-D case ν is zero.

The data of the pressure fluctuations for testing models are obtained in a wind tunnel. They are measured by pressure tubes at a sampling frequency of 100 Hz. The pressure tubes were placed on a NACA 0015 aerofoil with a chord length of 1m and a span of 2m. The measurements are used to calculate the lift and the spectrum of the lift fluctuations by integration and Fourier analysis, respectively.

2 CONCLUSIONS

Figure 4 shows how the lift response by the models compares to data. It is seen that data is over the models. This is not expected because the model from [3] (red) is 1-D and is based on highly anisotropic turbulence. The 2-D model ([4], blue) is based on isotropic turbulence and the data are known to be obtained at slightly anisotropic turbulence. The spectrum of the data is thus expected to be in between the models.

BIBLIOGRAPHY

[1] P. Moriarty and P. Migliore, Semi-Empirical Aero acoustic Noise Prediction Code for Wind Turbines, 2003, NREL/TP-500-34478.

[2] R. K. Amiet, Acoustic Radiation From An Airfoil In A Turbulent Stream, 1975, J. Sound and Vibr., **41**(4), 407-420.

[3] W. R. Sears, Some Aspects of Non-Stationary Airfoil Theory and Its Practical Application, 1941, J. of the Aeronatical Sc., Vol. 8, No. 3, 104-108.

[4] J. M. R. Graham, Lifting Surface Theory for the Problem of an Arbitrarily Yawed Sinusoidal Gust Incident on a Thin Aerofoil in Imcompressible Flow, 1971, The Aeronautical Quart., 182-198.

Offshore Wind Speeds – Modelling and Forecasting the Wind Resources over the North Sea

Jens Tambke[1)]

[1)] ForWind, University of Oldenburg, Germany

ABSTRACT

Long term assessment and short term predictability of marine wind speeds and wind power is crucial for its economic success. In this work, the effects of different factors on the accuracy of the forecasts were analysed, e.g. different weather models, their combination and spatial smoothing of errors. It was shown that mesoscale models for the marine atmospheric flow can simulate the wind speeds properly and allow for the correct prediction of temporal power gradients. For a detailed simulation of the vertical profiles, a new analytic model was developed and evaluated with Horns Rev and FINO1 data. In particular, the flux of momentum through the Ekman layers of the atmosphere and the sea is described by a common wave boundary layer.

KEYWORDS

Offshore, Resource Assessment, Short-Term Prediction, Forecasting, Vertical Wind Profile

1 OFFSHORE WIND SPEED PROFILES

To achieve precise wind resource assessments, to calculate loads and wakes as well as for reliable short-term wind power forecasts, the vertical wind profile above the sea has to be modelled with high accuracy for tip heights up to 160m. For these purposes, it is crucial to consider the special meteorological characteristics of the marine atmospheric boundary layer. This work investigates marine wind speed profiles that were measured at the two met masts Horns Rev (62m high) and FINO1 (103m) in the North Sea. Pronounced effects of thermal stratification and of the influence of the land-sea transition were analysed. In many situations, the wind shear is significantly higher than expected with standard approaches. Nevertheless, the numerical analysis of the marine wind field above the North Sea from the German Weather Service (DWD) seems to provide a good assessment of wind speeds at 103m height. For an improved simulation of the vertical wind speed profiles, a new analytic model of marine wind velocity profiles was developed. In particular, the flux of momentum through the Ekman layers of the atmosphere and the sea is described by a common wave boundary layer. The good agreement between the theoretical profiles and observations at FINO1 support the basic assumption of the model that above the sea surface, Ekman layer conditions begin at lower heights than 100m.

jens.tambke@uni-oldenburg.de

2 FORECASTING OFFSHORE WIND POWER

In accordance with previous evaluations of offshore wind power forecasts, this work with FINO1 data has shown that offshore power forecasts based on DWD weather predictions have a normalised RMSE of 15-27% of the rated power for 3-48h. This is comparable or better than onshore accuracy, especially with regard to the mean *producible* power, which is twice as high as onshore. It is important to note that comparisons with onshore forecasts have to consider this different average power *output*, not only the rated power.

A comparison at FINO1 shows that ECMWF outperforms DWD with an RMSE of 13% to 22%. A weighted combination reduces the error with a factor of 0.94. Nevertheless, ECMWF forecasts show an underestimation of temporal wind speed gradients due to the coarser resolution in space and time.

The regional forecast for a total (simulated) capacity of 25GW in the German Bight shows an RMSE of 9% to 17%, credited to spatial smoothing effects that reduce the error with a factor of 0.73 compared to a single site. Hence, a regional forecast for all offshore sites based on a DWD-ECMWF input combination would show an RMSE of 12% at 36h forecast time, i.e. an absolute RMSE of 3GW. The increase of the spatial error smoothing with the size of the region also holds for a simulated 50GW ensemble of onshore and offshore wind farms in Germany. The area size of 800km leads to an error reduction factor of 0.43. With a single site error of 16% at 36h forecast time, this would result in a relative RMSE of 7% and an absolute RMSE of 3.4GW for a total installed capacity of 50GW, which shall be realised in the coming decades.

Overall Dynamics and Integrated Design of Offshore Wind Turbines

Jan Quappen

Endowed Chair of Wind Energy at the Institute of Aircraft Design,

Universität Stuttgart, Germany

ABSTRACT

The complex and nonlinear dynamic behaviour of offshore wind turbines can be analysed by using an integrated simulation approach in the time domain. However, the existing models for large offshore turbines, loaded by stochastic wind and waves are not validated by full scale measurements yet.

The final objective of the project is to compare simulation results of the Multibrid M5000 turbine including the support structure, with measurements which will be carried out at the onshore prototype and the offshore wind farm Alpha Ventus. The gained experience will be used for the further development of an integrated design approach for offshore wind turbines including their support structures.

KEYWORDS

offshore wind turbine, support structure, integrated design, load validation, design approach, FLEX5

1 INTRODUCTION

For the large number of planned offshore wind farms, that will be build in the North Sea and the Baltic within the next decades, there will be an increasing need for validated design methods to facilitate the cost effective and reliable design of offshore wind turbines.

The complex and nonlinear behaviour of offshore wind turbines can be very well modelled by using an integrated simulation approach in the time domain. However, there are no validated models of multi-MW offshore turbines up to now. To overcome this, the behaviour of the Multibrid M5000 turbine and its support structure simulated with the FLEX5 code should be compared with measurement data at the wind farm alpha ventus, which is currently under construction in the North Sea.

quappen@ifb.uni-stuttgart.de

2 DESICRIPTION OF FUTURE WORK

The aim of this PhD-project is to come up with new or further developed methods for the integrated design procedure of offshore wind turbines with special focus on their support structures. Therefore, different models adapted to specific stages of the design process should be taken into account. The first task within the project will be the validation of aero-elastic models for the 5MW wind turbine class onshore. By using those validated aero-elastic models, the overall dynamics of the Multibrid M5000 turbine and its tripod support structure should be verified and compared to measurements at the onshore prototype.

Further on, the specific behaviour of the Multibrid M5000 turbine assembled on a tripod support structure based offshore should be analysed and evaluated. Therefore, load signals derived by simulations or measurements for different support structures or locations will be compared to each other. An emphasis of the work is to specify the interactions of the rotor-nacelle assembly with the behaviour of the support structure.

The work is a part of research project OWEA (Verification of Offshore Wind Turbines), founded by the BMU (German Federal Ministry for the Environment, Nature Conservation and nuclear safety) in the scope of the RAVE Program (Research at Alpha Ventus).

3 OBJECTIVES AND EXPECTED RESULTS

It is expected, that the comparison of measurement data with the simulated response of the Multibrid M5000 will lead to more detailed knowledge about the dynamic behaviour of offshore wind turbines in general. Thus, the design procedure might be simplified or at least improved, due to a better understanding of interactions within the entire offshore wind turbine system.

By combining the results gained from simulations with measurement data, a validated turbine model should be build up for offshore conditions. These results will make it possible to check and if necessary adjust the currently used design codes as well as the presently applied design methods and guidelines.

Simulations with solution based mesh adaptation for fluid structure interactions

J.J.H.M. Sterenborg[1], A.H. van Zuijlen[2], H. Bijl[3]

[1] PhD-researcher, [2] Assistant professor, [3] Full professor

Technical University of Delft, Department of Aerodynamics, the Netherlands

ABSTRACT

Simulations of multi-physics systems are time consuming and therefore acceleration techniques are commonly used. The current research focuses on the application of solution based mesh adaptation to fluid structure interaction (FSI) computations. The FSI-solver used in this work is a partitioned solver that consists of a RANS solver for the flow and a rigid body solver for the structure. The aim is to assess the gain in efficiency when using solution based mesh adaptation in combination with FSI. Thereby, the number of time steps between successive adaptations and the number of adaptation steps per adaptation are considered. Preliminary results indicate the potential of the method, since flow features are resolved more detailed with the same number of cells.

KEYWORDS

Fluid Structure Interactions, Unsteady solution based mesh adaptation, RANS

1 INTRODUCTION

It is well known that for a correct and efficient design of flexible structures, fluid structure interactions should be considered. This is one of the current issues in the field of wind energy, since due to the increased size of wind turbines blades, flexibility issues are non-negligible.

Although the computer capacity has improved, the simulations of fluid structure interaction systems require large computational times and are inherently expensive. Therefore, more research is needed to find options to reduce the computational times of such simulations. Since for (un)steady computations it is proven that solution based mesh adaptation increases the efficiency [1], it is investigated if the application of unsteady solution based mesh adaptation to FSI computations also leads to an increase in efficiency.

j.j.h.m.sterenborg@tudelft.nl

2 MESH ADAPTATION FOR FSI

2.1 Unsteady solution based mesh adaptation

Mesh adaptation concerns the modification of an existing mesh with the aim to increase the computational efficiency and accuracy. The modifications can be based on a known solution on the current mesh, such that regions where small scale flow features are present will be refined and regions where only large scale features are present will be coarsened. In this way, with a reduced number of cells it is possible to maintain the accuracy of the solution and a gain in efficiency should therefore be possible.

Drawback is that the modification of the mesh increases the computational time. This means that the application is only advantageous when the efficiency gain by the cell reduction exceeds the reduction in efficiency due to the re-meshing. For unsteady computations, it is therefore not trivial that the most beneficial solution is to adapt the mesh each time step.

The solution based mesh adaptation is based on error indicators that are a measure of the discretization error. In this work, for all cell faces the $\log_2$ value of the error indicator is computed and stored in bins [2]. Depending on the threshold value for refinement/coarsening, all cells in a particular bin can be flagged for adaptation. The $\log_2$ scaling prevents over-refinements of regions where severe flow features are present and the consequence that other important flow features are not resolved properly. Furthermore, it enables to compute threshold values based on the target number of cells after adaptation, since an estimate of the number of cells after adaptation can be made a priori.

The error indicator is a finite difference formulation based on one or more flow variables, multiplied by a factor which is based on the spatial resolution. In the preliminary computations the pressure gradient is taken as sensor and the error indicators are defined by:

$$\varepsilon = \Delta\left(\left\|\nabla p\right\|\right) \cdot h_{sd}^{x}. \qquad (1)$$

In this equation ∇p is the pressure gradient, h_{sd} is the minimum distance between the face and the neighbouring cell centers and x is a power term for the distance. The minimum distance h_{sd} is used to prevent over-refinements by an underestimation of the error indicator in case large cell size jumps occur. Thereby, for small values of x the adaptations are performed locally, whether for large values of x more global adaptations are allowed. A value of $x = 1.5$ is established to give the most satisfying results [3],[4].

For now, in this preliminary work only refinements are possible. Unsteady simulations have been performed, where the average of error indicators over a time period is used to perform one adaptation sequence. Subsequently, the same computation is executed again with the new mesh. In order to have an adaptation algorithm that can be applied more efficiently to unsteady flows, coarsening must be available as well. Currently, coarsening is being implemented.

2.2 FSI solver

For the flow, a Reynolds Averaged Navier Stokes (RANS) solver in combination with the one equation Spalart Allmaras turbulence model is used. The structure is assumed rigid, which simplifies the structural model to a system of equations of motion. The FSI solver is of the partitioned type, meaning the flow and structure are solved subsequently. In this work, the structure and the flow are solved only once per time step (loosely coupled). This reduces the computational time, but is less accurate. The mesh movement is performed by making use of Radial Basis Function (RBF), to determine the flow-structure interface displacements.

3 TEST CASE: VISCEL

The test case is derived from the VISCEL project part II [5]. A rigid NACA 0012 airfoil section is modelled that can move in the chord wise direction (edge wise) and in the direction perpendicular to it (flap wise). In Figure 1 a schematic overview is presented of the structural model.

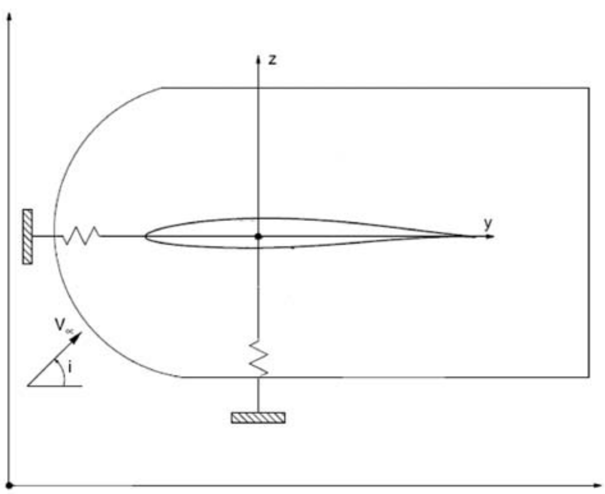

Figure 1: Structural model

The equations of motion for this system are given by:

$$\begin{bmatrix} \rho_s & 0 \\ 0 & \rho_s \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{z} \end{Bmatrix} + \begin{bmatrix} k_y & 0 \\ 0 & k_z \end{bmatrix} \begin{Bmatrix} y \\ z \end{Bmatrix} = \frac{1}{2} \rho_a \overline{V}^2 c \begin{Bmatrix} f_y \\ f_z \end{Bmatrix}, \tag{2}$$

where f_y and f_z are aerodynamic coefficients, $(\dot{\ })$ is differentiation with respect to the time and all the other variables are presented in Table 1 and Table 2. Furthermore, the structural stiffnesses k_y and k_z are defined by:

$$\begin{aligned} k_y &= \rho_s \omega_y^2, \\ k_z &= \rho_s \left(\omega_z^2 + \Omega^2 \right). \end{aligned} \tag{3}$$

The variables ω_y and ω_z are the natural frequencies in the edge wise and flap wise direction and Ω represents the rotational velocity of the rotor.

Table 1: Settings flow solver

Parameter	Used Settings
Initial angle of attack α_0	$18°$
Initial y-position y_0	0 m
Initial z-position z_0	0 m
Initial y-velocity $\dot{y}_0$	0 m/s
Initial y-velocity $\dot{z}_0$	0 m/s
Reynolds number Re_c	2×10^6
Ambient pressure p	101325 Pa
Kinematic viscosity ν	1.716×10^{-5} m^2/s
Density ρ_a	1.224 kg/m^3
Undisturbed flow velocity $\overline{V}$	34.32 m/s
Mach number Ma	0.1
Ratio spalart viscosity and kinematic viscosity $\tilde{\upsilon}/\upsilon$	0.1
Chord c	1 m

Table 2: Settings structure solver

Parameter	Used Settings
Mass ρ_s	61.2 kg
Stiffness in y-direction k_y	35321.938 N/m
Stiffness in z-direction k_z	12254.480 N/m

4 CONCLUSIONS

Results will be presented that follow from the preliminary work where only refinements are possible. Since no proper benchmark case is available yet, a qualitative review is given. Considered are two vorticity plots: one is for a manually made grid with 65k cells, the other is for a 32k mesh that is adapted (2x) to a 65k mesh. The adaptation is based on the largest error indicators of a FSI computation of 1 second physical time. In Figure 2 the two vorticity plots are given for t = 0.27s.

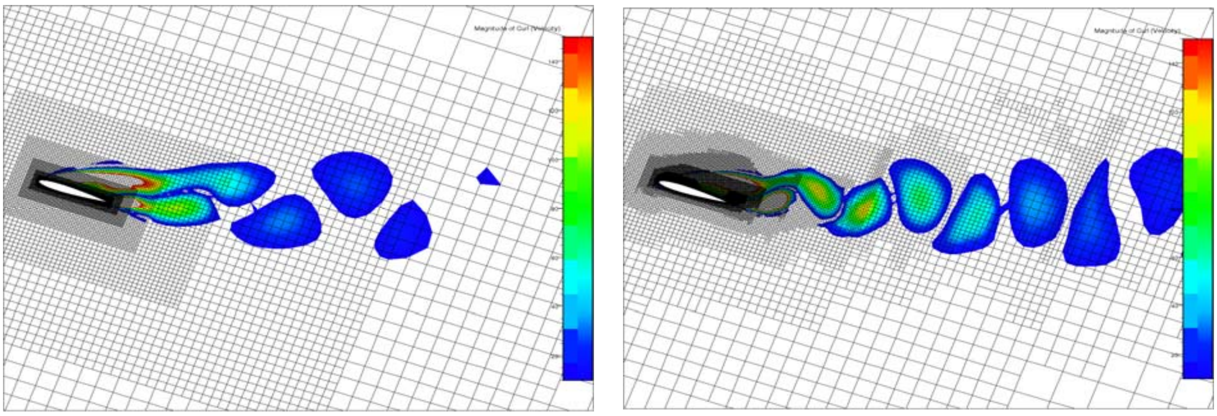

Figure 2: Differences in the solution between an non-adapted (left) and adapted grid (right) of both 65k cells

Three important aspects can be seen in figure 2. Firstly, it can be seen that the strength of the vorticity is better preserved in case the adapted grid is used. Secondly, flow details are better resolved for the adapted grid. Thirdly, the adapted regions can be seen clearly: close to the airfoil and in the wake area adaptations are performed.

The preliminary results are promising and therefore the adaptation routine is currently extended with coarsening capabilities in order to make it able to perform multiple adaptations during the unsteady computation.

BIBLIOGRAPHY

[1] Gardner, A., Richter, K. and Rosemann, H., ‘’Simulation of Oscillating Airfoils and Moving Flaps Employing the DLR-TAU Unsteady grid adaptation’’, New Results in Numerical and Experimental Fluid Mechanics VI, pp 170-177, Vol. 96/2008, 2007.

[2] Aftosmis, M. and Berger, M., ‘’Multilevel Error Estimation and Adaptive *h*-refinement for cartesian Meshes with embedded boundaries’’, AIAA, Vol. 2002-0863, 2002.

[3] Lucas, P., ’’An automated approach to optimize numerical accuracy for a given number of grid cells applied to Cartesian grids’’, Master's thesis, Delft University of Technology, 2005, http://www.aero.lr.tudelft.nl/education/pdf/2005 1 03.pdf.

[4] Lucas, P., "An automated approach to optimize numerical accuracy for a given number of grid cells applied to Cartesian grids’’, Submitted to: International journal for numerical methods in fluids, 2006.

[5] Chaviaropoulos, P. et al., ‘’Viscous and aeroelastic effects on wind turbine blades: VISCEL project partII’’, Wind Energy, 2003.

Wind Turbine Modeling for Transient Analysis: Application to the Spanish Grid Code

Antonio J. Pujante López[1)], Emilio Gomez Lázaro[1)], Juan Álvaro Fuentes[2)]

[1)] Renewable Energy Research Institute. Universidad Castilla La-Mancha, Spain,

[2)] Universidad Politécnica de Cartagena, Spain

ABSTRACT

The aim of this paper is the implementation of a dynamic model of a DFIG variable speed wind turbine where all the parameters are known and that can be used for different types of dynamic studies as, for example, the evaluation of its transient state and steady state response, using different control strategies, when it is submitted to any type of fault, and in this type of events are studied the compliance degree of the imposed requirements by the Spanish Grid Code. Another application of the above DFIG model is that it can also be used as a building block for creating an aggregated model of a wind farm and, thus, studying the behaviour of the whole wind farm under such faults.

KEYWORDS

Wind turbine, DFIG, power system control, voltage dips, grid codes.

1 INTRODUCTION

In order to obtain this base model, an extensive bibliographical search has been carried out. As a result, different sets of parameters that may be used to model the wind generator have been found and the values used for both, the electrical and mechanical part of the model, have been compiled. It should be highlighted that for a specific set of parameters it has been difficult to find numerical values, above all the mechanical part, as it is the case of [13]. Nevertheless, [12] offers an appropriate range of values of the mechanical parameters of a DFIG with a given nominal power. On the other hand, not all the parameters found are given in pu, as is the case with the mechanical parameters, and the range of their magnitudes can be very different. It has to be said that only those machines whose nominal power are in the range of the typical DFIG wind generators normally installed at present in wind farms are considered.

2 DFIG MODEL

The selected DFIG wind generator model used in this paper, machine number 11, has been chosen from the most complete set of parameters presented in Tables I and II.

AntonioJesus.Pujante@uclm.es, Emilio.Gomez@uclm.es, JuanAlvaro.Fuentes@upct.es

Machine	Power (MW)	Un (kV)	Rs (pu)	Rr (pu)	Lm (pu)	Lsl (pu)	Lrl (pu)	fn (Hz)	Np	Ns/Ns
1	0.85	0.69	0.006	0.009	4.238	0.072	0.112	50	2	< 1
2	0.85	0.69	0.004	0.006	2.724	0.046	0.072	50	2	< 1
3	0.85	0.69	0.01554	0.01165	5.3115	0.0689	0.11167	50	2	< 1
4	0.85	0.69	0.027	0.021	11.403	0.125	0.204	50	2	< 1
5*	2	0.69	0.01	0.0086	4.4	0.18	0.074	50	2	0.4
6	2	0.69	0.00488	0.00549	3.953	0.09241	0.09955	50	2	< 1
7	2	0.69	0.0175	0.019	6.921	0.2571	0.295	50	2 o 3	0.4333
8	2	0.69	0.0108	0.0121	3.362	0.102	0.11	50	2 o 3	0.38
9	2	0.69	0.09841	0.00549	3.9527	0.1248	0.09955	50	2	0.643
10	2	0.69	0.00488	0.00549	3.9527	0.1386	0.1493	50	2	0.45
11	2	0.69	0.0488	0.018	3.8	0.075	0.12	50	2	<1

Table I. Electrical parameters of the induction machines.

Machine	Power (MW)	Turbine / Generator Inertia Constant (s)		Lumped Inertia Constant (s)	Shaft Stiffness Constant (pu/rad)	Damping Coefficient (pu)
1	0.85	4.17	0.54		1.16	
2	0.85			5.23		
3	0.85	4.790	0.4790		0.5806	0
4	0.85	4	0.3		1.0	
5*	2	2.5	0.5		0.3	
6	2			3.5		
7	2			4.0712		0.02
8	2			3		
9	2					0.02
10	2			3.5		
11	2	2.5	0.5		2.5	

Table II. Mechanical parameters of the induction machines.

Once having selected a set of mechanical and electrical parameters, the wind turbine model has been implemented in commercial simulation software and the results obtained from the different simulations of such DFIG wind turbine generator are presented.

The electrical circuit used in the simulations consists of the following components: the wind turbine model, the typical rotor and grid side power converters, the grid transformer, the crowbar protection circuit and the control scheme related to the power converters. In relation to the DC-link capacitor and the input AC inductive filter, conservative values have been used in order to ensure the stability of the system.

3 CONCLUSIONS

The results obtained in the simulations of the DFIG model are analyzed for several implemented control strategies, keeping in mind the imposed requirements by the P.O. 12.3.

BIBLIOGRAPHY

[1] John Tande, Ian Norheim, "Benchmark test of dynamic wind generation models for power system stability studies," IEA Wind R&D Annex 21, p. 9, 2006.

[2] J.O Tande, E. Muljadi and B. Lemstrom., "Dynamic models of wind farms for power system studies, status by IEA wind R&D annex 21," in European Wind Energy Conference and Exhibition (London)., 2004.

[3] Petersson, A.; Thiringer, T.; Harnefors, L.; Petru, T., Modeling and experimental verification of grid interaction of a DFIG wind turbine," IEEE Transaction on Energy Conversion, vol 20, pages 878 - 886, 2005.

[4] Joris Soens, Karel de Brabandere, "Doubly fed induction machine: Operating regions and dynamic simulation," EPE, pp. 1–10, 2003.

[5] A. Petersson and T. Thiringer, "A DFIG wind turbine ride-through system. influence on the energy production," WIND ENERGY (Wiley Interscience), vol. 8, p. 251-263, 2005.

[6] L. Holdsworth, X.G. Wu and N. Jenkins, "Direct solution method for initialising doubly-fed induction wind turbines in power system dynamic models," IEE Proceedings Generation, Transmission & Distribution, vol. 150, pp. 334 – 342, 2003.

[7] F. Tao Sun; Zhe Chen; Blaabjerg, "Flicker study on variable speed wind turbines with doubly fed induction generators," IEEE Transaction on Energy Conversion, vol. 20, pp. 896 – 905, 2005.

[8] H. Yikang, H. Jiabing, and Z. Rende, "Modeling and control of wind turbine used DFIG under network fault conditions," Electrical Machines and Systems, Proceedings of the Eighth International Conference on, vol. 2, pp. 986– 991, 2005.

[9] J. Zou, Heping Sun, "Fault ride-through performance of wind turbine with doubly fed induction generator," Industrial Electronics and Applications, 2007. ICIEA 2007. 2nd IEEE Conference, pp. 1607–1611, 2007.

[10] T. Dawei Xiang, Li Ran and S. Yang, "Control of a doubly fed induction generator in a wind turbine during grid fault ride-through," IEEE TRANSACTIONS ON ENERGY CONVERSION, vol. 21, pp. 652– 662, 2006.

[11] A. Perdana and J. Persson, "Dynamic response of grid-connected wind turbine with doubly fed induction generator during disturbances," in NORDIC WORKSHOP ON POWER AND INDUSTRIAL ELECTRONICS. TRONDHEIM, 2004.

[12] T. Ackermann, Wind Power in Power Systems. John Wiley & Sons, Ltd., 2005.

[13] M. Burgos J.C, Arnalte S., "Optimización del rendimiento de un generador asíncrono de doble alimentación en sistemas de generación eólica de velocidad variable".

Wind Turbine Load Reduction by Learning the Periodic Load Disturbance

I. Houtzager[1], J.K. Rice[1], J.W. van Wingerden[1], and M. Verhaegen[1]

[1] Delft Center for Systems and Control, Delft University of Technology, The Netherlands

ABSTRACT

The trend in offshore wind turbines is to increase the rotor diameter as much as possible to decrease the cost per kWh. The increasing dimensions have led to a relative increase of the loads on the wind turbine structure, thus it is necessary to react to disturbances in a more detailed way: each blade separately. The disturbances acting on an individual wind turbine blade are to a large extent deterministic; for instance the tower shadow, wind shear, yawed error and gravity, which depend on the rotation angle and speed. A repetitive controller can learn these periodic disturbances for fixed-speed wind turbines and variable-speed wind turbines operating above-rated. The performance of the controller is evaluated on a simplified first-principle model, which describes the most relevant periodic dynamics of the wind turbine in a linear-parameter-varying framework. Simulation results indicate that for relatively slow changing disturbances this method can significantly reduce the vibrations in the wind turbine structure.

KEYWORDS

repetitive control, lifted LQG design, individual pitch control, load reduction, blade vibration

1 INTRODUCTION

The main disadvantage of wind energy is that it is still more expensive than its fossil fuel alternatives. The reason is that the foundation costs of offshore wind turbines amount to a large part of the total costs, therefore designers want to increase the energy yield as much as possible to reduce the costs. To maximize the energy yield, the rotor diameter must be increased as much as possible; hence, modern wind turbines have become the largest rotating machines on earth, with a rotor diameter larger then the wingspan of an Airbus A380. With the increase in rotor size and the relocation offshore, where large wind farms are developed due to less restricting planning constraints, but maintenance is difficult and expensive, the importance of active reduction of fatigue loads will increase.

Most modern large wind turbines run at variable rotational speed, and allow the adjustment of the collective pitch angle of the blades to optimize energy yield and to control the loads [1]. The control of the blade pitch angle has not only led to power regulation, but also to a

I.Houtzager@TUDelft.nl

significantly lighter blade construction due to the lower load spectrum and a lighter gear box due to shaved torque peaks. The collective pitch control method assumes that the same wind gusts are active on the whole rotor area; therefore it can only handle slow wind changes that have an effect on the entire rotor. As the rotor size increases, the wind speed variation across the rotor swept area becomes larger. Thus for further load reduction it is necessary to react to wind speed variations in a more detailed way: each blade separately and at several separate radial distances. To further minimize the loads, the latest development in the wind turbine industry (motivated by the helicopter industry) is Individual Pitch Control (IPC) [2–4].

The load disturbances acting on an individual wind turbine blade are to a large extent deterministic, such as the tower shadow, wind shear, yawed error and gravity, and they depend on the rotation angle and speed. The contribution of these periodic disturbances is becoming larger, due to the increasing length and mass of the rotor blades. This paper contributes to the development of IPC by proposing a Repetitive Control (RC) design method which can deal with this kind of periodic disturbances for fixed-speed wind turbines and variable-speed wind turbines operating above-rated. For relatively slow changing periodic disturbances it is expected that this control method can significantly reduce the vibrations in the wind turbine structure.

2 THE DISTURBANCES ENCOUNTERED BY THE BLADE DURING THE ROTATION

In the lower layers of the atmosphere the wind speed is mainly influenced by the friction with the surface of the earth. The roughness of the landscape, like buildings and trees, could reduce the wind speed considerably and increase turbulence. Two important wind effects created by obstructions in the airflow near the wind turbine are called wind shear and tower shadow. Wind shear is the variation in height of the average undisturbed wind velocity, see Figure 2. Tower shadow is the distortion of the average undisturbed wind speed caused by the presence of a support structure in the wind flow, see Figure 3.

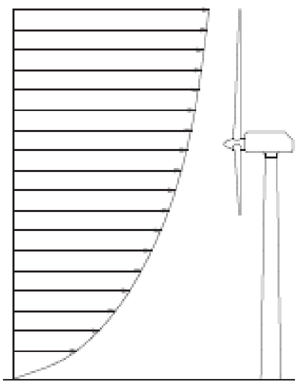

Figure 1: The left side view of a modern HAWT, showing the wind shear effect.

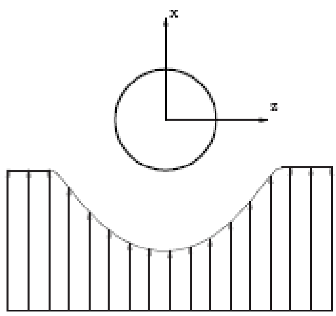

Figure 2: The top view of a cross section from the tower, showing the tower shadow effect.

The slicing of the wind by the rotating blades transforms the wind load spectrum seen by the rotating rotor by additional excitation of energy at rotor frequency 1P (once-per-revolution) and its multiples. It has been experienced that small three-bladed wind turbines have mostly 3P, 6P and 9P fluctuations on the drive shaft and structure, because the three blades will tend to cancel the small 1P and other components [2]. As turbines are becoming larger, the 1P component becomes larger, because wind shear and gravity loads increases.

3 REPETITIVE CONTROLLER DESIGN

In the previous section it has been explained that the disturbances acting on an individual wind turbine blade are to a large extent periodic. For relatively slow changing periodic disturbances it is expected that RC can significantly contribute to the reduction of fatigue of the wind turbine parts. The RC system rejects the unknown periodic disturbances by means of individual blade pitch action. The repetitive controller is added to the closed-loop wind turbine system as an additional output-feedback loop; see the block diagram illustrated in Figure 4. The goal is to design an input sequence u^{RC} to reject the repetitive (and unknown) wind disturbances, such that the system output becomes closer and closer to a given desired output trajectory *r* from trial-to-trial.

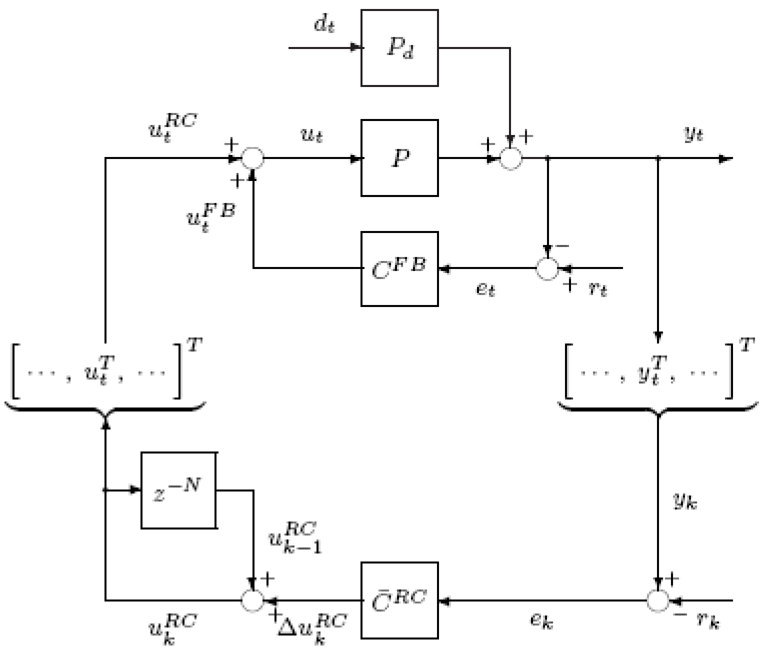

Figure 3: Block diagram of the closed-loop wind turbine system with RC output-feedback loop and one memory loop added. The abbreviation P stands for the plant dynamics, C^{FB} stands for the feedback controller, and C^{RC} stands for repetitive controller.

The RC is designed by formulating a lifted output-feedback problem is formulated such that after a full rotation (trial) the input signal is updated to counteract the described periodic disturbances. For the transition from trial-to-trial, a “lifted” model is derived based on the periodic time-varying state-space model of the system under study. Using LQG controller design methods, a feedback controller is designed to deal with the stability of the system and the stochastic disturbances. Therefore, the repetitive controller is designed “on top” of the closed-loop wind turbine system. To design an update law which is guaranteed stable, the dynamics of the feedback controller have to be included in the output-feedback problem. In the deterministic case, excluding non-repetitive disturbances, the algorithm will converge exponentially fast to zero. In the case of white noise disturbance in the plant model, the RC algorithm can minimize the variance of the resulting tracking error.

The biggest problem of implementing this RC description of the output-feedback problem is that the lifted matrices are enormous, and it will take a long time to solve. This issue is resolved by exploiting the matrix structure. In [7], efficient methods for solving Riccati equations using the so-called Sequentially Semi-Separable (SSS) matrix structure and its properties are discussed. Iterative algorithms exist to check matrix stability, to solve Lyapunov and Riccati equations, and to compute LQG controllers in computational complexity. Also the structured repetitive controller can be implemented using structures matrix-vector computations in computational complexity and memory storage.

The other main drawback of RC is that the performance strongly depends on the precise match between the controller’s period and the actual period of the disturbance signal. With even a slight period mismatch, the performance of the controller can decrease substantially. An important extension to standard RC is given in [9], where multiple memory loops are used to make RC more robust to small changes in period-time of the disturbance signal. Using this extension, the application of RC to wind turbines with small variations in rotational speed, such as variable-speed operating above-rated, becomes more practical.

4 SIMULATION STUDY

In this paper we consider a five degrees of freedom model, as described in [4,5,10]. The model describes the rotational dynamics of a wind turbine around a particular operating point. The model contains degrees of freedom for the main rotation, first torsion mode of the drive train, the first fore-aft, and sideward bending mode of the tower. In this model, the blades are considered to be rigid. The feedback controller used during simulation can be found in [5], where the collective pitch controller and generator torque controller are parameterized. To fulfill the assumption that the RC has at least as many trial inputs as trial outputs, the controlled inputs of the plant are chosen to be the generator torque and the pitch angle of each rotor blade, and the controlled outputs to be the generator speed and the blade root bending moment of each rotor blade.

From Figure 4-7 it is shown that using RC reduces considerably the effect of the wind shear and tower shadow compared to the system with only a feedback controller (FB). In Figure 4 the initial response of the first blade root moment is illustrated. The additional pitch input of the RC, illustrated in Figure 5, gives after a number of trials a considerable reduction in the amplitude. As described in Section 2, these periodic disturbance effects result in additional excitation of energy at rotor frequency 1P (once-per-revolution) and its multiples. In Figure 6 the power spectral density from the output of the first blade root moment is illustrated. The additional excitation at 1P, 2P, and 3P frequencies are clearly visible in the response with only feedback control. Using RC these effects are totally gone. Similar results are given in Figure 7, where the power spectral density from the output of the fore-aft velocity is illustrated. In the simulations the 1P and 2P effects on the three blades caused by wind shear and tower shadow results mostly in 3P and 6P effects on the wind turbine structure, for example the tower.

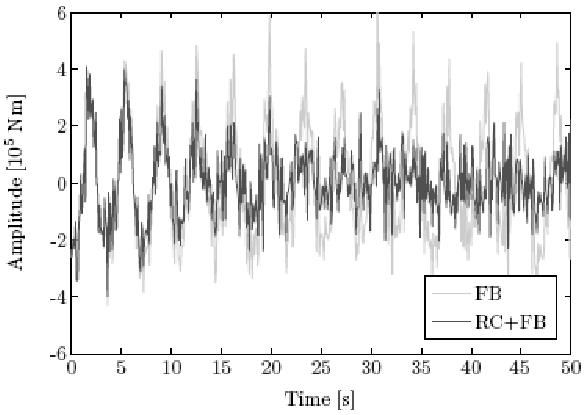

Figure 4: Illustration of the initial response of the first blade root moment.

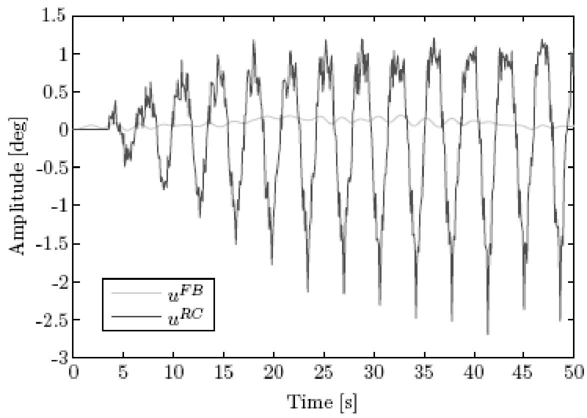

Figure 5: Illustration of the pitch input angles of the first blade using RC.

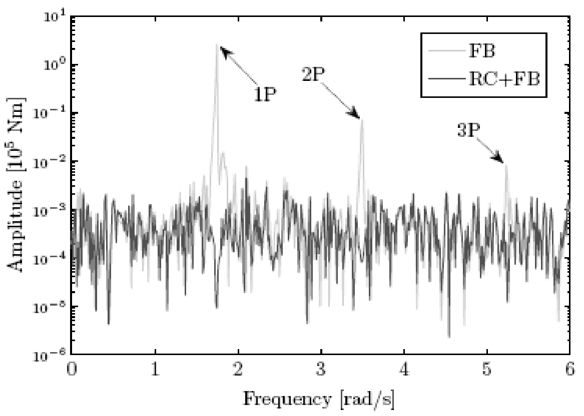

Figure 6: Illustration of the power spectral density from the output of the first blade root moment over 100 trials.

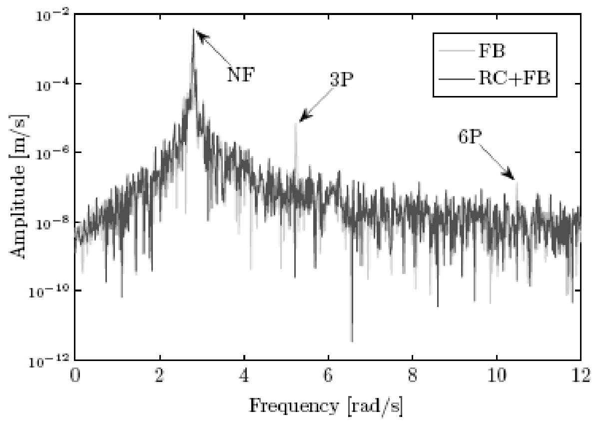

Figure 7: Illustration of the power spectral density from the output of fore-aft velocity over 100 trials. The abbreviation NF stands for the first natural frequency of the tower.

5 CONCLUSIONS

This paper contributes to the development of individually pitch controlled blades by proposing a repetitive controller that can learn these periodic disturbances for fixed-speed wind turbines and variable-speed wind turbines operating above-rated. The special SSS matrix structure of the repetitive control system has been exploited to find a LQG solution with guaranteed exponential convergence in only linear complexity, allowing this method to be used on trials with large samples. The implementation of such controller is also of linear computational complexity and memory allocation. The performance of the controller is evaluated on a simplified first-principle model, which has most relevant periodic dynamics of the wind turbine described in a linear-parameter-varying framework. Simulation results indicate that for relatively slow changing disturbances this method can significantly contribute to the reduction of vibrations in the wind turbine structure. A reduction of these cyclic loads can lead to weight savings and to an increase in the life span of wind turbines.

BIBLIOGRAPHY

[1] Bossanyi, E. A., The design of closed loop controllers for wind turbines, Wind Energy 3, 2000, 149-163.

[2] Bossanyi, E. A., Individual blade pitch control for load reduction, Wind Energy 6, 2003, 119-128.

[3] Bossanyi, E. A., Further load reduction with individual pitch control, Wind Energy 8, 2005, 481-485.

[4] van Engelen, T., Design model and load reduction assessment for multi-rotational model individual pitch control, European Wind Energy Conference, 2006.

[5] van Engelen, T., et. al., Morphological study of aeroelastic control concepts for windturbines, Technical report, Energy Research Center (ECN), 2007.

[6] Larsen, T.J., Madsen, H.A, Thomsen, K., Active load reduction using individual pitch, based on local blade flow measurements, Wind Energy 8, 2005, 67-80.

[7] Rice, J.K., Verhaegen, M., Repetitive learning control for stochastic LTV systems, submitted to Automatica, 2008.

[8] Selvam, K., et al., Feedback-feedforward individual pitch control for wind turbine load reduction, International Journal of Robust and Nonlinear Control, Special Issue on Control of Wind Turbines. 2008.

[9] Steinbuch M., Repetitive control for systems with uncertain period-time, Automatica 38, 2002, 2103–2109.

[10] van Wingerden, J. W., et. al., Closed-loop identification of the time-varying dynamics of variable-speed wind turbines, International Journal of Robust and Nonlinear Control, Special Issue on Control of Wind Turbines. 2008.

Validation of a CFD wake model based on the actuator disk technique and the thrust coefficient. Preliminary results

Daniel Cabezon[1], Javier Sanz[1], Ignacio Martí[1], Antonio Crespo[2]

1) Wind Energy Department, National Renewable Energy Centre (CENER), Spain

2) Departamento de Ingeniería Energética y Fluidomecánica, Escuela Técnica Superior de Ingenieros Industriales, Universidad Politécnica de Madrid (UPM)

ABSTRACT

A simplified CFD wake model based on the actuator-disk concept is used to simulate the wind turbine, represented by an actuator disk upon which a distribution of forces, defined as axial momentum sources, are applied on the incoming flow. The rotor is supposed to be uniformly loaded, with the exerted forces as a function of the incident wind speed, the thrust coefficient and the rotor diameter. The model is validated through experimental measurements downwind of a wind turbine in terms of wind speed deficit. Validation on turbulence intensity will also be made in the near future.

KEYWORDS

Actuator disk, thrust coefficient, turbulence modelling

1 INTRODUCTION

Wind turbine rotor effect has been modelled using several types of approaches, from analytical engineering models to the 3D CFD full rotor modelling [1]. During the last years and due to the need of modelling the far wake and wind turbines interaction in challenging environments such as complex terrain and offshore, new proposals have arisen through the so-called 'back to the basics' concept. An elliptical approach based on coupling the actuator disk technique and CFD can make a fair simplification of the rotor without leaving the main essence of its physics. This paper represents the first stage of a series of single-rotor validation processes of this technique for different turbulence model parametrizations in order to optimize more advanced releases for modelling wakes interaction in wind farms.

2 NUMERICAL MODELLING

A non-uniform flow is modelled in a computational domain (30Dx7.5Dx5D) representing the surface boundary layer, in which the Monin-Obukov theory is solved from the Reynolds Average Navier Stokes equations and the turbulent transport terms from the k-ε method. The wind turbine is considered as an actuator disk upon which uniformly distributed forces, defined as axial momentum sources, are applied.

dcabezon@cener.com

3 RESULTS

A three bladed Nibe-B 630 kW wind turbine with a 40m diameter and located at hub height of 45m is simulated. An upstream velocity of 8.5m/s and a turbulence intensity of 11% is used for the incoming flow, giving a value of C_t=0.82 for the axial thrust coefficient at the rotor [2].

Different parametrizations of the 2 equations k-ε turbulence model are used in order to control the excess of turbulent diffusion in the wake and therefore the wind speed deficit and added turbulence intensity. A compromise must be found between the optimum parameters for the modelling of the wind at the surface boundary layer and the rotor wake aerodynamics.

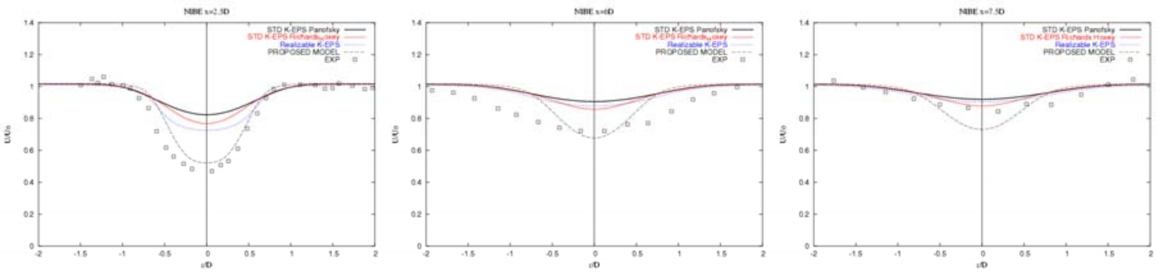

Figure 1: Wind speed deficit at the wake of Nibe-B wind turbine rotor

The proposed model is based on the work of El Kasmi et. al. [2] and Chen and Kim [3] but corrected by using a set of constants which keeps the hypothesis of equilibrium in the wall. The model is compared with other configurations of the standard k-ε turbulence model (set of constants proposed by Panofsky and Richards-Hoxey) and with the realizable k-ε turbulence model. A good agreement is found for the proposed model on the first sections, whereas in the far wake some deviations start making the other options more appropriate.

4 CONCLUSIONS

A validation of an elliptic model based on the actuator disk technique and thrust coefficient is presented. The results are especially sensitive to the parametrization of the turbulence model, with deviations depending on the type of modelling and on whether it is near or far wake. Further work will consist on extending the validation to other experimental cases with different turbulence model parameters preserving the accuracy of ABL wind simulation and optimize multi-rotor configurations in order to analyze wakes interaction inside wind farms.

BIBLIOGRAPHY

[1] Vermeer L.J. et. al., 2003, Wind turbine wake aerodynamics. Prog. Aerosp. Sci. 39, 467-510

[2] El Kasmin A., Masson C., An extended k-ε model for turbulent flow through horizontal-axis wind turbines, J. Wind Engineering and Industrial Aerodynamics 96 (2008), 103-122

[3] Chen Y.S., Kim S.W., 1987. Computation of turbulent flow using an extended turbulence closure model. NASA Contractor Report, NASA CR-179204

[4] Crespo, Manuel and Hernández "Numerical modelling of wind turbine wakes". European Community Wind Energy Conference Proceedings, Madrid, September 1990

[5] España G., Laporte L., Wind turbine wake characteristics in an Atmospheric Boundary Layer. Far Wake Physical and Numerical Modelling, Proceedings of EWEC 2008, Brussels (Belgium)

Sea State and Wave Load Modeling in WaveLoads 2.0 and its Application in a Multibody Simulation Framework

Thomas Kossel, Martin Kohlmeier, Werner Zielke

ForWind – Center for Wind Energy Research

Institute of Fluid Mechanics, Leibniz Universität Hannover, Germany

ABSTRACT

WaveLoads is a software for calculation of wave induced loadings on hydrodynamicially transparent structures such as monopiles, tripods and jackets of OWECs – developed at the Institute of Fluid Mechanics, Leibniz Universität Hannover. Various wave models for uni- and multidirectional sea states are implemented to provide appropriate load prediction.

The latest developments have been focused on integrating WaveLoads in simulation frameworks. Interfaces to FE programs such as ANSYS, Abaqus or MSC Nastran have been further extended. A multibody simulation framework using Adams, FAST/AeroDyn and a DLL-version of WaveLoads gave the opportunity to investigate both the interaction of the wind field and the rotor blade dynamics as well as the influence of wave loading estimated in different sea states.

KEYWORDS

wave load, sea state modeling, simulation framework for offshore wind energy converters.

1 INTRODUCTION

The design optimization of the support structure of offshore wind energy converters (OWEC) is a key issue towards cost efficient offshore wind energy projects. Meeting these demands requires a reliable simulation framework reflecting the entire OWEC system, including the structural dynamics of the system, the load and control interaction and finally the impact on the foundation. WaveLoads is a software for calculation of wave induced loadings on hydrodynamically transparent structures such as monopiles, tripods and jackets of OWECs.

2 WAVE LOAD SIMULATION

Loads due to water waves represent a significant part of the total environmental loads of OWECs – especially in deep water. Profound understanding of different sea states and adequate wave simulation are essential for a reliable design basis.

Waves entering shallow water show an increase in nonlinear behavior resulting in steeper crests and shallower troughs accompanied by a change in water particle kinematics. Usually,

kossel@hydromech.uni-hannover.de

these waves are approaching the shore line in a more or less unidirectional way. In deeper water the direction and the spreading of the waves are varying according to the current sea state. In WaveLoads wave models for various uni- and multidirectional sea states are implemented to provide appropriate load prediction.

3 SIMULATION FRAMEWORK FOR OWECS

The latest developments of WaveLoads have been focused on the integration in simulation frameworks. Interfaces to FE programs have been further extended. A complete transient analysis with adjacent post-processing can be performed using WaveLoads' interface to ANSYS, Abaqus or MSC Nastran. The required interfaces to integrate WaveLoads as a load generation module in simulation frameworks, are provided by a dynamic link library (DLL) that has been developed. As an application a multibody simulation framework has been set up using Adams, FAST/AeroDyn and WaveLoads. This approach gives the opportunity to investigate both the interaction of the wind field and the rotor blade dynamics as well as the influence of wave loading estimated in different sea states (Fig. 2).

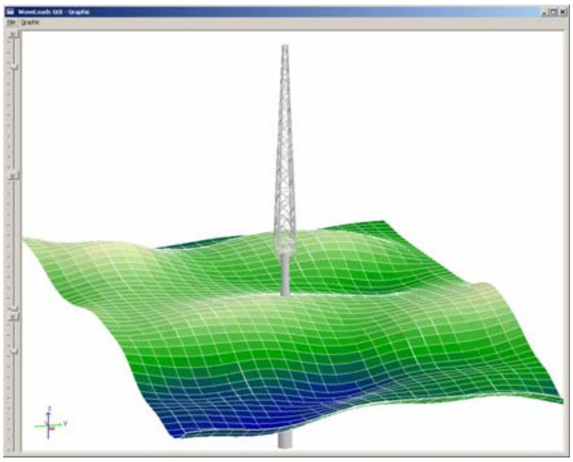

Figure 1: Water surface of a generated directional sea state (elevation scaled by 4) with measuring mast Amrumbank West

Figure 2: Wind and wave loads acting on an exemplary offshore wind turbine

4 CONCLUSIONS

This paper deals with the simulation of wave induced loads on OWECs using the load generator WaveLoads. Different wave models implemented in WaveLoads provide appropriate load prediction for various uni- and multidirectional sea states. The development of different interfaces enable WaveLoads to be integrated in simulation frameworks. An application is given in a multibody simulation framework that provides the opportunity to investigate the interaction of the components and the influence of different load cases.

Large Eddy Simulations of an Airfoil in Turbulent Inflow

Lasse Gilling[1)] and Niels N. Sørensen [1,2)]

[1)] Aalborg University, Denmark, [2)] RISØ-DTU, National Lab. for Sustainable Energy, Denmark

ABSTRACT

Wind turbines operate in the turbulent boundary layer of the atmosphere and due to the rotational sampling effect the blades experience a high level of turbulence [1]. In this project the effect of turbulence is investigated by large eddy simulations of the turbulent flow past a NACA 0015 airfoil at Reynolds number 1.6 million. The effect of increasing the turbulence intensity is investigated and the results are compared to measurements from a wind tunnel. By including the inflow turbulence the agreement with measurements is improved for some angles of attack. The results indicate that the free stream turbulence may trigger separation of the flow at angles of attack close to stall.

KEYWORDS

Wind Turbine, Airfoil, Large Eddy Simulation, Turbulence, Wind Tunnel

1 INTRODUCTION

When designing an airfoil for a wind turbine blade the performance of the airfoil can typically be predicted by experiments and two-dimensional steady Reynolds Averaged Navier-Stokes (RANS) simulations. For low angles of attack RANS predicts the lift and drag with high accuracy because the flow is two-dimensional and steady [2]. For high angles of attack near or after stall the flow is three-dimensional and unsteady which leads to poor accuracy of RANS. These effects can be captured by a detached eddy simulation (DES) where the largest eddies in the separated area are resolved.

Detached eddy simulation (DES) is a hybrid of RANS and large eddy simulation (LES) [3]. It was developed for airfoil flows and has been successfully applied to different airfoils at a great range of angles of attack [4, 5]. In a typical DES the inflow turbulence cannot be resolved because the grid is very coarse in the upstream part of the domain. This is not the case for a LES.

In the present paper LES will be applied to airfoil flows in a wind tunnel. The effect of inflow turbulence will be investigated and the lift, drag and pressure distribution on the airfoil will be compared to experimental results.

lg@civil.aau.dk

2 COMPUTATIONAL SETUP

The RISØ-DTU/DTU flow solver EllipSys3D is used in all computations presented in the following. The code is developed by the Department of Mechanical Engineering at the Technical University of Denmark and The Department of Wind Energy at Risø National Laboratory, see [6-8].

The computational setup is shown in Figure 1. The geometry of the setup is chosen to match the layout of the wind tunnel. The airfoil is a NACA 0015 with chord c. The outlet is placed 25c downstream from the airfoil and the domain is 1.5c in the spanwise direction. The wall boundary layer at the profile is modelled by the DES-technique. The Reynolds number is 1.6 million and the resolved domain contains 21 million cells.

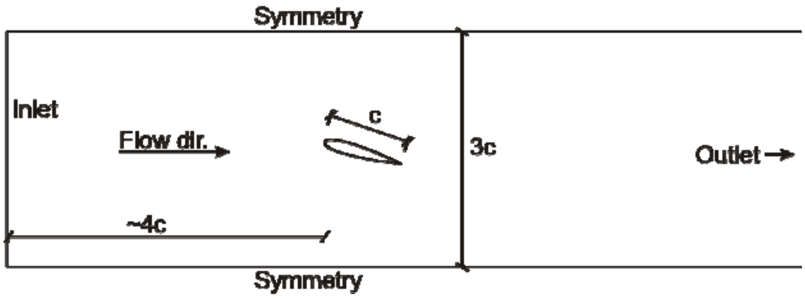

Figure 1: Computational setup

The inlet boundary condition is a mean velocity superposed by a turbulence field. The turbulence is generated synthetically and run through a precursor simulation.

3 RESULTS

The experimental results are reported in [6]. In Figure 2 the lift and drag coefficients are shown for different turbulence intensities. The turbulence intensity in the wind tunnel is approximately 0.1 %. The length scale of the turbulence in the simulations is roughly 0.25c.

The Figures 3 and 4 show the time averaged pressure distribution for 14° and 16° angles of attack.

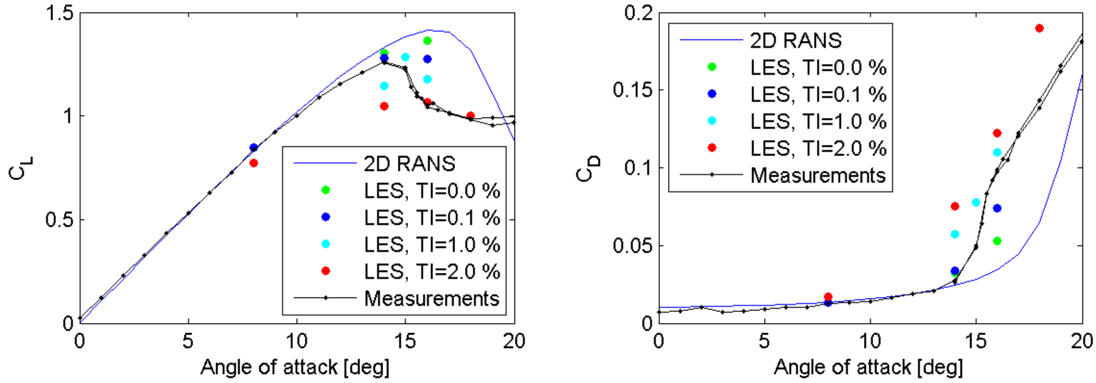

Figure 2: Lift and drag coefficients vs. angle of attack

The agreement between measured and experimental data is seen to be improved by including turbulence in the simulations. For 8° and 14° angle of attack a turbulence intensity of 0.0-0.1 % gives the best agreement with experiments. For 16° angle of attack 2% turbulence intensity gives better agreement. The pressure distributions for 15° at 1.0 % and 18° at 2.0 % turbulence intensity (not shown) are in good agreement with experimental results.

The two-dimensional RANS shows good agreement with measurements for low angles of attack but fails to predict the lift and drag close to and after stall.

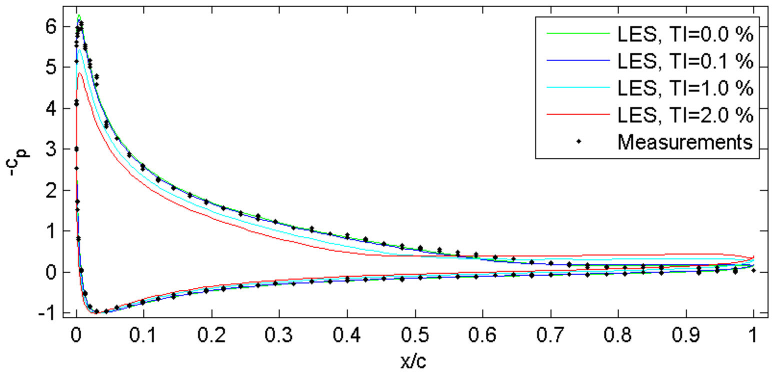

Figure 3: Pressure coefficient for 14° angle of attack

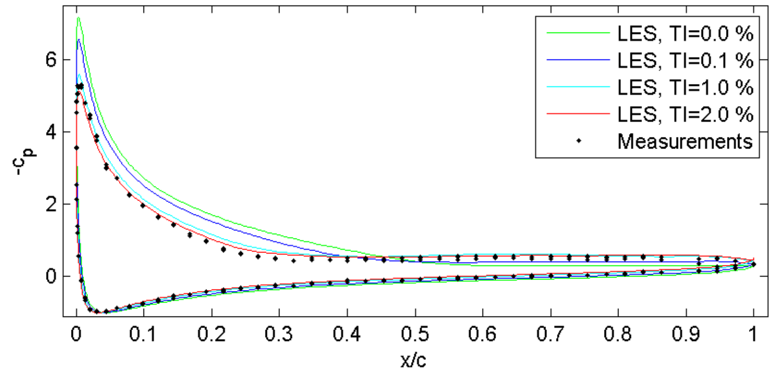

Figure 4: Pressure coefficient for 16° angle of attack

4 CONCLUSIONS

From the above results it is seen that the free stream turbulence has a large influence on the flow at angles of attack near stall. At these incidences the turbulence can cause the flow to separate.

The turbulence intensity that gives best agreement with measurements is not constant for different angles of attack. A reason for this could be that the turbulence intensity in the measurements may vary with the angle of attack due to increased loading of the fan or due to disturbances from the wake partially surviving the tour round the closed circuit tunnel.

Further work includes simulations with intermediate turbulence intensities and other angles of attack. These will form a base for the decision on whether or not further experiments are needed to determine the turbulence intensity and length scale in the wind tunnel more accurately.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the experimental data supplied by the wind turbine blade manufacturer LM Glasfiber. This work was funded by the Danish Council for Strategic Research under the project “Airfoils in Turbulent Inflow”.

BIBLIOGRAPHY

[1] Connell, J. R., “The Spectrum of Wind Speed Fluctuations Encountered by a Rotating Blade of a Energy Conversion System,” *Solar Energy* **29**(5), pp. 363–375, 1982.

[2] Bertagnolio, F., Sørensen, N. N., and Johansen, J., “Profile Catalogue for Airfoil Sections Based on 3D Computations” Tech. Rep. Risø-R-1581(EN), RISØ National Laboratory, Roskilde, 2006.

[3] Spalart, P. R., Jou, W.-H., Strelets, M., and Allmaras, S. R., “Comments on the Feasibility of LES for Wings, and on a Hybrid RANS/LES Approach,” 1st AFOSR International Conference on DNS/LES, pp. 137–147, August 1997.

[4] Strelets, M., “Detached Eddy Simulation of Massively Separated Flows,” AIAA Paper 2001-0879, 2001.

[5] Shur, M., Spalart, P. R., Strelets, M., and Travin, A., “Detached-Eddy Simulation of an Airfoil at High Angle of Attack” Engn. Turbulence Modelling and Experiments, Vol. 4, pp. 669–678, 1999.

[6] Michelsen, J.A.. Basis3D - a Platform for Development of Multiblock PDE Solvers. Technical Report AFM 92-05, Technical University of Denmark, 1992.

[7] Michelsen J.A., ”Block structured Multigrid solution of 2D and 3D elliptic PDE's”, Technical Report AFM 94-06, Technical University of Denmark, 1994.

[8] Sørensen, N.N.. General Purpose Flow Solver Applied to Flow over Hills. Risø-R-827-(EN), Risø National Laboratory, Roskilde, Denmark, June 1995.

[9] Bove, S., “LSWT Report of Campaign NACA 0015_1,” Tech. rep., LM Glasfiber, Lunderskov, 2008.

Planned Implementation of a Navier-Stokes based Immersed Boundary Method for Simulation of Moving Trailing Edge Flaps on a Wind Turbine Blade

Tim Behrens[1,2)]

[1)] Vestas Wind Systems A/S, Aero-Systems, Denmark

[2)] Department of Mechanical Engineering, Technical University of Denmark, Denmark

ABSTRACT

For future generation wind turbines, the use of trailing edge flaps (TEF) is a promising way to reduce loads [1] and influence blade stability. To calculate the flow around TEF, different approaches like moving and overlapping grids are being conducted. Another possibility is to use the immersed boundary method (IBM) introduced by Peskin [2] in 1972. Here, the solid boundaries are not represented by the body-fitted mesh faces, but by forcing terms in the governing equations. The aim of this work is to implement the IBM into the flow solver EllipSys [3] and extend it to very high Reynolds numbers as experienced on wind turbine blades.

KEYWORDS

Immersed boundary method, trailing edge flaps, load reduction, high Reynolds numbers

1 INTRODUCTION

To decrease the cost of wind energy further, it is essential to reduce loads on turbine and blades by managing aerodynamic loads induced by large scale turbulence. This will allow larger rotor diameter, reduce material consumption, reduce turbine distance in parks and allow better performance in complex terrains. To achieve these goals, wind turbine blades with trailing edge flaps are a promising solution under research at the moment [1].

The Adaptive Trailing Edge Flap (ATEF) project is a collaboration of *Technical University of Denmark (DTU), Risø-DTU* and *Vestas Wind Systems A/S* with financial support from *Danish National Advanced Technology Foundation (Højteknologifonden).* Within this project, research is conducted on aerodynamics, actuators and controls of TEF. The aim of the project it to demonstrate the feasibility of flaps implemented on wind turbine blades and in the near future there will be a demonstrator test on a Vestas V27 turbine (225 kW).

tibeh@vestas.com

On the CFD part, calculations of moving TEF in wind energy as well as in aeronautic research have been carried out mostly on moving or overlapping grids used in potential flow solvers as well as Navier-Stokes (NS) solvers. In the current work, the immersed boundary method, first introduced by *Peskin* [2], will be implemented into the existing incompressible NS flow solver EllipSys [3] and extended to a degree where it is able to handle high Reynolds number flows on wind turbine blades.

2 IMMERSED BOUNDARY METHOD

A summary of IBM can be found in *Mittal and Iaccarino* [4]. In the following a short introduction to the conceptual idea shall be given. The incompressible Navier-Stokes equations read

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) + \nabla p - \mu\Delta\vec{u} = \vec{f} \tag{1}$$

$$\nabla\cdot\vec{u} = 0 \tag{2}$$

Where $\vec{u}$, ρ, p, μ, t are the velocity, density, pressure, viscosity and time respectively. $\vec{f}$ is a forcing term which represents the immersed boundary on the RHS of equation (1) to satisfy the no-slip condition. This forcing can be applied by a sharp Dirac delta function or smoothed out over a certain distance.

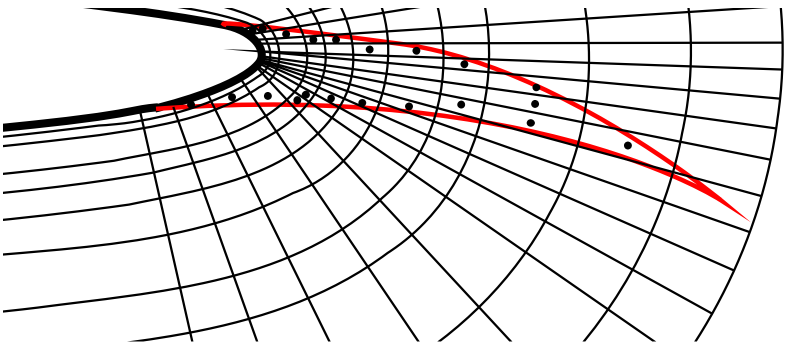

Figure 1: Sketch of mesh (-) in the trailing edge region; body-fitted boundary (-) ; immersed boundary (-) ; forcing points ●

3 APPLICATION

In this work a code with discrete forcing approach and direct boundary condition imposition via forcing points will be used. The basic procedure is to find the forcing cells, i.e. cells inside the body with neighbouring fluid cells (Fig.1). Afterwards fluid quantities will be interpolated to impose no-slip condition at the boundary location.

Immersed boundary methods are mainly used on Cartesian grids to use faster solving algorithms. In this work standard structured grids will be used. Only the moving boundaries of the trailing edge flap will thereby be represented by forcing points in the immersed boundary method (Fig. 1).

The biggest challenge for IBM application to high Reynolds number flows is the turbulence modelling at the boundary. Here interpolation methods and modelling of thin objects like sharp - in relation to mesh cell dimensions - trailing edges need careful consideration. Also grid point distribution at the trailing edge needs to be adapted.

The first part of this work is to enable the EllipSys flow solver to make use of immersed boundaries with the needed accuracy. The integration of sufficient interpolation methods and turbulence modelling for high Reynolds regime are the main challenges.

The final aim is to couple the CFD calculations with controller algorithms that are currently being developed within ATEF project and generate the aerodynamic coefficients for changing inflow conditions.

4 CONCLUSIONS

This paper gave a short introduction to the immersed boundary method, current problems for applications in the high Reynolds number regime of wind turbine blades. An outline was given of the future work that will be done to support development of trailing edge flaps on wind turbines.

5 ACKNOWLEDGEMENTS

This work is partially funded by Danish National Advanced Technology Foundation (Højteknologifonden).

BIBLIOGRAPHY

[1] Buhl, T.; Gaunaa, M.; Bak, C.: Load Reduction Potential Using Airfoils With Variable Trailing Edge Geometry, AIAA-2005-1183, American Institute of Aeronautics and Astronautics, 2005

[2] Peskin, C.S.: Flow patterns around heart valves: a digital computer method for solving the equations of motion. PhD thesis. Physiol., Albert Einstein Coll. Med., Univ. Microfilms, 1972

[3] Sørensen, N. N.: General Purpose Flow Solver Applied to Flow over Hills, Risø-R-827, Risø National Laboratory, Roskilde, Denmark, 2003

[4] Mittal, R.; Iaccarino, G.: Immersed Boundary Methods, Annual Review of Fluid Mechanics, vol. 37, pp. 239-261, 2005.

Investigation of Coupling of EMC Disturbances in Wind Generators with DFIG

Sebastian Schulz, Andreas Lindemann

Otto-von-Guericke-University Magdeburg, Institute of Electric Power Systems, Germany

ABSTRACT

In wind farms doubly fed induction generators (DFIG) are used, where the stator of the generator is directly connected to mains, while the converter for the rotor is rated only for slip power. Using a rotor converter, harmonics and conducted emissions have to be considered, taking into account that harmonics – which can be limited by filters – will also be transmitted into the stator.

KEYWORDS

wind energy, doubly fed induction generator, harmonics, conducted emissions, power quality

1 INTRODUCTION

The exploitation of renewable energy has increased significantly in the last years. A major contribution is related to wind energy. One intent of the energy production is high yield as achievable by variable speed operation. This requires to use a converter. The high frequency and fast changing output voltage of the converter can cause conducted emissions and system perturbation which will be considered in the following.

2 COUPLING OF WIND POWER SYSTEM

2.1 Possibilities of grid coupling

Wind turbines are based on synchronous or induction generators. To supply the energy of the generators into the grid it is common to use a power converter [1]. There are two possibilities:

- power converter for the full rated power, cf. the topologies in Figure 1a, c, d)
- power converter for the rotor of a DFIG – only to be rated for slip power, cf. Figure 1b)

Sebastian.Schulz@ovgu.de

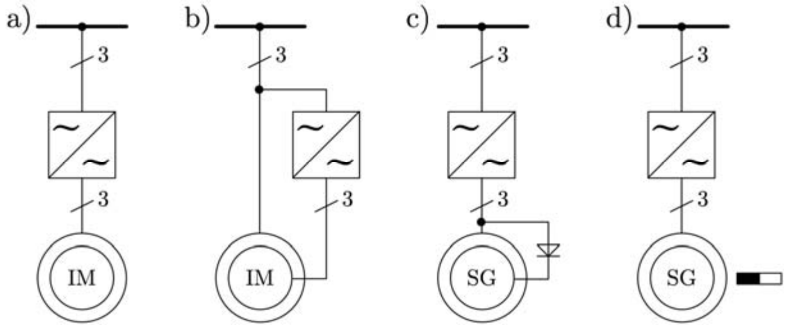

Figure 1: Possibilities of grid coupling

Generally speaking, care must be taken to comply with the EMC regulations for grid connection. Filters may be used to compensate harmonics; however they reach a considerable size and cause considerable cost at high power ratings of the converter generating them.

2.2 Grid coupling of doubly fed induction machine

Using a doubly fed induction generator (DFIG), stator of the machine is directly connected to the mains. The converter for the rotor is only rated for slip power which is about 30% of the nominal power of the DFIG. This topology thus can inherently decrease the EMI-level because of the lower power rating of the rotor converter compared to a converter for full rated power. This kind of system according to Figure 2 allows a large speed range of about 70% to 130% of the nominal rotor speed for optimized wind power generation [2].

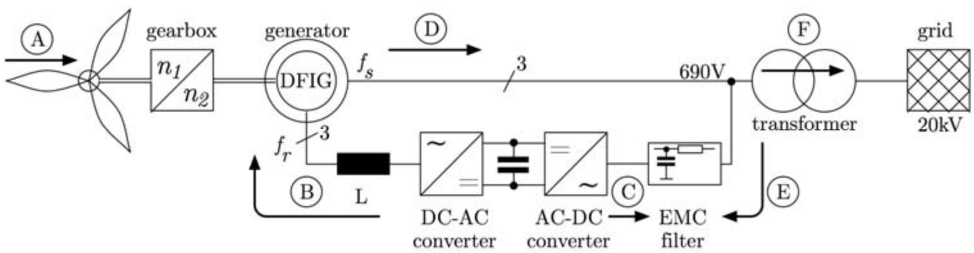

Figure 2: Doubly fed induction generator for wind power generation (DFIG)

3 SYSTEM PERTURBATION OF DFIG

3.1 EMI sources

When using a fast switching high frequency converter, high voltage rise rates (du/dt) of the basically rectangular output voltages occur. Capacitive leakage currents and conducted emissions can be determined. Figure 2 shows several possibilities for the emergence and propagation of conducted emissions: High frequency pulsed rotor voltages cause harmonics of the rotor currents (B) which are transferred to the stator current (D); considering the slip of the generator, sub harmonics will occur. The stator current supplies the transformer, thus the harmonics and sub harmonics will proceed to the grid (F). The implemented EMC filter is mostly intended to reduce the additional conducted emissions of the rotor converter on transformer side (C). Emissions of stator current are hardly affected by this filter.

Electromagnetic compatibility aspects of conducted emissions and system perturbation of power converters are regulated in the grid connection regulations of the transmission system operator [3], EN 61000 [4][5], EN 61800-3 [6] and EN 50160 [7]. The emission limits set by this standard correspond with limits of the fundamental EMC standard EN 55011 [8].

3.2 Simulation

3.2.1 Simulation model

Figure 3 shows the configuration of the simulated wind power system. The stator shall feed a power of 12 kW into the line sources (u_{e1}, u_{e2}, u_{e3}). The rotor current i_r of the DFIG is supplied by a converter. It is nearly sinusoidal but will include harmonics given by the modulation of the rotor converter. Mechanically, the rotor is driven by a torque of 76 Nm; it rotates with 1527 1/min. Note that the relatively low power level has been chosen to facilitate comparison with experimental results according to section 3.4.

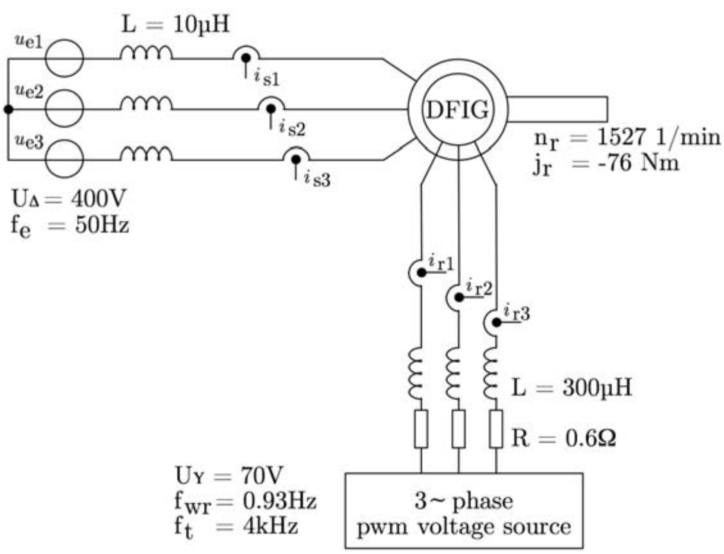

Figure 3: Simulation model of doubly fed induction generator (DFIG)

3.2.2 Simulation results

The simulation results correspond excellently to the theoretically expected waveforms. As shown in figure 4, the three-phase rotor current and stator current are nearly sinusoidal. While stator frequency corresponds to mains frequency of 50 Hz, rotor frequency is low.

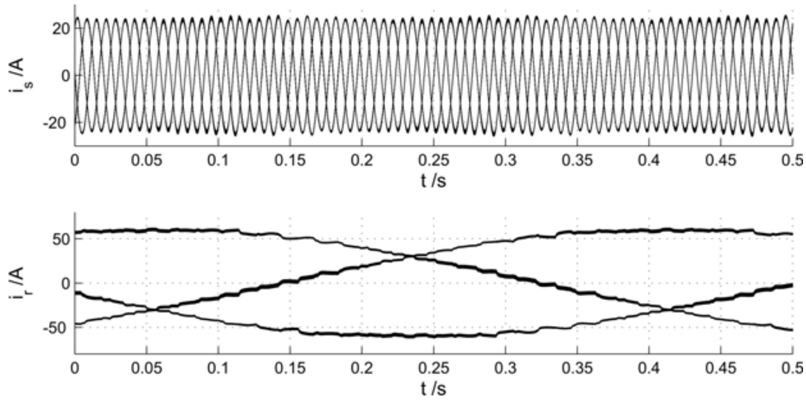

Figure 4: Simulated stator current i_s and rotor current i_r for one rotor period

More detailed simulation results are shown in figure 5a). The harmonics generated by the 4kHz pulsed rotor converter appear in the rotor current i_r as well as in the stator current i_s . This result illustrates that the harmonics are transmitted by the magnetic field, i. e., the waveform of simulated stator current i_s shows the transmitted harmonics into the stator windings. FFT analysis in figure 5b) again shows the harmonics caused by pulsed rotor converter.

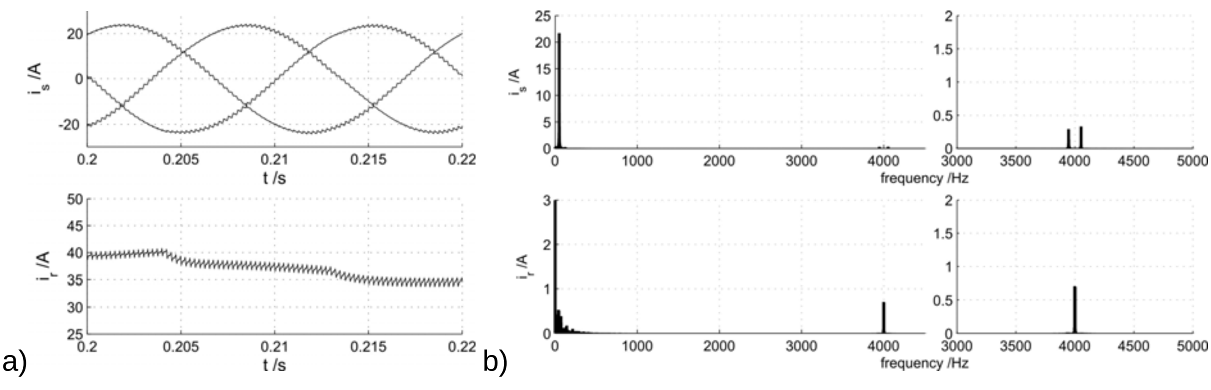

Figure 5: Simulation of a) stator current i_s , rotor current i_r ,
b) FFT of the simulated stator current i_s , rotor current i_r

3.3 Circuit theory – equivalent circuit of a doubly fed wound rotor induction machine

The single phase equivalent circuit of a doubly fed induction machine according to figure 6 corresponds to a transformer's, where the equations of Faraday's law of induction apply:

$$u_s = i_s \cdot (R_1 + j\omega_1 L_{1\sigma}) + u_\mu \quad (1)$$

$$\frac{u'_r}{s} = i'_r \cdot \left(\frac{R'_2}{s} + j\omega_1 L'_{2\sigma} \right) + u_\mu \quad (2)$$

$$u_s = i_s \cdot (R_1 + j\omega_1 L_{1\sigma}) - i'_r \cdot \left(\frac{R'_2}{s} + j\omega_1 L'_{2\sigma} \right) + \frac{u'_r}{s} \quad (3)$$

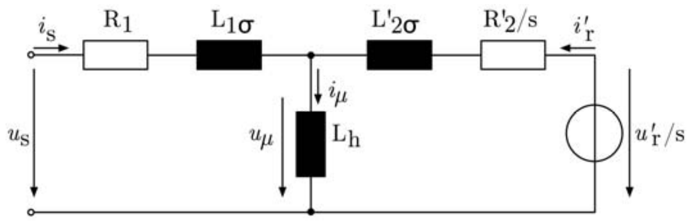

Figure 6: One phase equivalent circuit of a DFIG [9][10]

Harmonics in rotor voltage u_r / s caused by the converter will cause harmonics in rotor and stator currents. Mains current of the DFIG thus is a superposition of a sinusoidal current with high frequency harmonics. The conducted emissions and harmonics depend on the pulse pattern of the rotor converter, the frequency and eventual rotor filter and the line filter of the wind power system.

3.4 Experiment

3.4.1 Experimental setup

To investigate the effect of the transmitted high frequency harmonics, an existing experimental setup according to figure 7 has been used: Here, the stator of the 11 kW DFIG is supplied by an AC-DC-AC power converter with a switching frequency of 4 kHz, while the wound rotor is short-circuited. The only filter elements are line inductors between converter and stator windings.

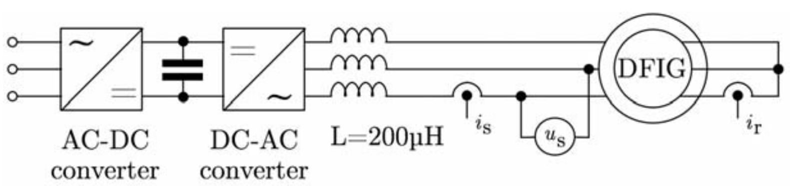

Figure 7: Experimental setup for driving a DFIG

3.4.2 Experimental results

According to the preceding considerations, harmonics in the stator currents of the experimental setup should cause harmonics in the rotor currents as well. Figure 8 shows one period of a rotor phase current i_r. The more detailed view in figure 9 - with waveforms over time and results of FFT analysis – illustrates that harmonics of all three stator currents – caused by their pulsed supply voltage – can be found in rotor current.

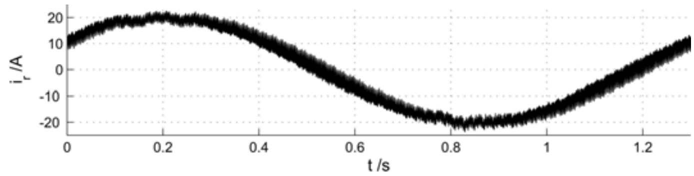

Figure 8: Measurement of rotor current i_r with superimposed pulses of the power converter

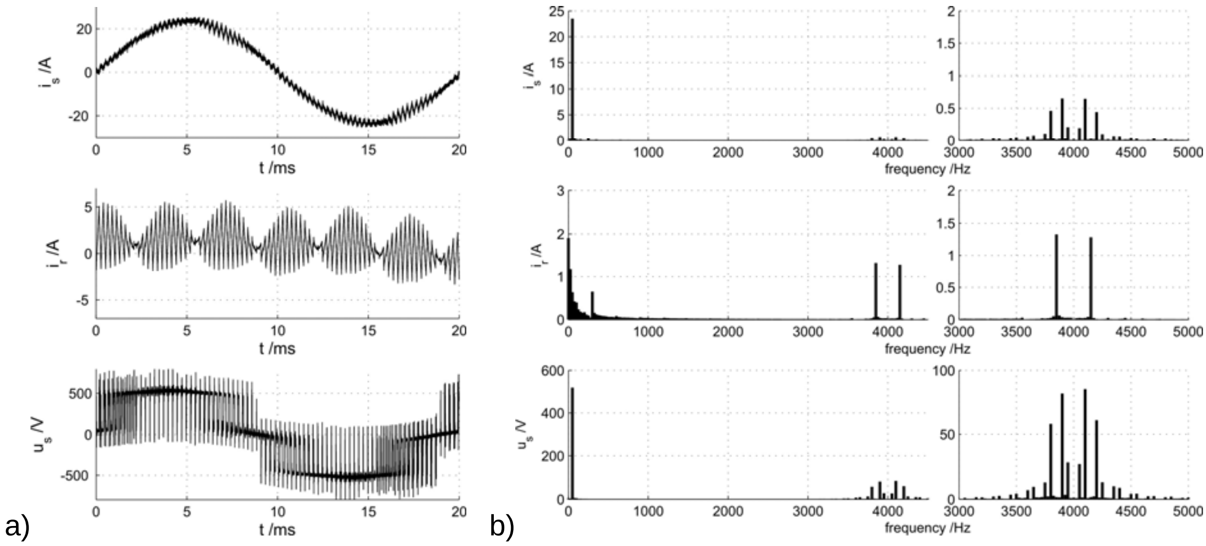

Figure 9: Measurement of a) stator current i_s , rotor current i_r , stator voltage u_s ,

b) FFT of the measured stator current i_s , rotor current i_r , stator voltage u_s

4 CONCLUSION

This paper deals with the interaction of rotor and stator winding in a doubly fed induction generator. High frequency harmonics caused by the pulsed output of rotor power converters are transmitted into the stator current and cause conducted emissions. It is possible to reduce them with filters in the rotor circuit, thus requiring a rating of only 30% of the nominal power.

BIBLIOGRAPHY

[1] Kimura, N.; Morizane, T.; Taniguchi, K.; Hamada, T.; Inverter Excited Induction Machine for High Performance Wind Power Generation System, EPE 2007, Aalborg

[2] Toufik, B.; Machmoum, M.; Poitiers, F.; Doubly Fed Induction Generator with Active Filtering Function For Wind Energy Conversion System, EPE 2005, Dresden

[3] E.ON Netz GmbH; Grid Connection Regulations for High end Extra High Voltage, Bayreuth, 2006

[4] Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current <= 16 A per phase) (IEC 61000-3-2:2005); German version EN 61000-3-2:2006

[5] Electromagnetic compatibility (EMC) – Part 6-4: Generic standards – Emission standard for industrial environments (IEC 61000-6-4:2006); German version EN 61000-6-4:2007

[6] Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods (IEC 61800-3:2004); German version EN 61800-3:2004

[7] Voltage characteristics of electricity supplied by public distribution networks; German version EN 50160:2007

[8] Industrial scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics – Limits and methods of measurement (IEC/CISPR 11:2003 + A1:2004, modified + A2:2006); German version EN 55011:2007 + A2:2007

[9] Sinelnikova, E.; Design und optimale Betriebsführung doppelt gespeister Asynchrongeneratoren für die regenerative Energieerzeugung, Dissertation, Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität Chemnitz, 2004

[10] Schröder, D.; Elektrische Antriebe – Regelung von Antriebssystemen; Springer Verlag; 2001

SESSION 2-A
WIND POWER GENERATION AND CONTROL

(Parallel to the Session 2-B)

Wednesday, 01.10.2008

14:00 – 16:40

Building 22A / Room 021 (H2)

Supervisor:

Prof. R. Rolfes, University of Hannover

Chairman:

A. L. Vernay, Delft University of Technology

Reactive Power Management and Voltage Control by the Wind Farm Cluster Management System

César Augusto Quintero Marrone

ISET e.V. Königstor 59 D-34119 Kassel / Germany

ABSTRACT

Main goal of this PhD Project is to develop a grid calculation module within the Wind Farm Cluster Management System (WCMS) that will perform the required load flow calculations. Thus, the dispatch of wind generators according to a given set point for the wind cluster can be determined. Based on these calculations, it is also possible to predict the possible reactive power provision for the cluster. The WCMS allows then the reactive power management to control reactive power, power factor and voltage changes as well as the active power generated from wind turbines according to the requirements of grid operators.

KEYWORDS

Wind power plant, grid integration, cluster, aggregation of wind farms

1 INTRODUCTION

The main goal for the implementation of the WCMS is to demonstrate the controllability of wind power under the concept of cluster aggregation according to the requirements of grid operators. Although developments in wind turbine technology have enabled single wind turbines and wind farms to follow determine set points issued by the grid operator, it is the main aim of the WCMS to achieve the controllability of wind power (control strategies) at a transmission grid node (cluster) level. Figure 1 depicts an overview of control strategies to be implemented with WCMS:

In figure 1, control strategies are divided on active and reactive power control for wind generation. Regarding the active power control, it is possible then to perform strategies such as wind power reserve, congestion management, power limitation and gradient control as required by the grid operator.

cquintero@iset.uni-kassel.de

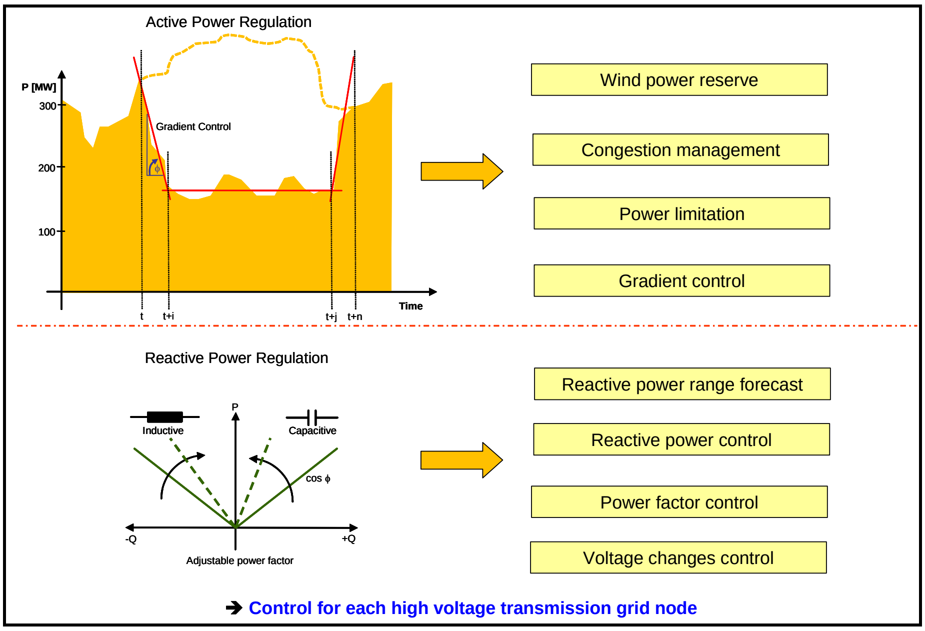

Figure 1: Overview of WCMS control strategies

By means of reactive power regulation, it is possible to control the power factor and voltage level changes at the connection point of the cluster. Due to the increasing capacity of wind energy in the grids, the reactive power feed-in has become an important aspect to consider due to grid operational security reasons. Therefore, it is necessary to design and develop a tool to perform an optimal management of the reactive power resource of the cluster.

Through a reactive power management tool within the grid calculation module of the WCMS, it is possible to perform scenarios based on real wind farm cluster data which lead to the determination of the available reactive power in a transmission node as well as the possible voltage changes caused by wind generation. Main purpose is also to determine the reactive and active power dispatch within wind farm aggregated by means of the cluster structure. These control strategies will be performed up to wind farm level; however they can be also implemented up to wind turbine level if it is required.

2 P/Q CAPABILITY CALCULATION

In order to perform a control strategy it is first necessary to determine the capability of active and reactive power (P/Q availability) at the point of common coupling of the cluster. The active power capability is obtained through the wind power forecast for the wind farm. On the other side, the reactive power capability is determined based upon the technical capabilities of the wind turbines within the cluster. The reactive power capability is described through the P/Q characteristic of the wind turbine. Figure 2 depicts a layout of this calculation.

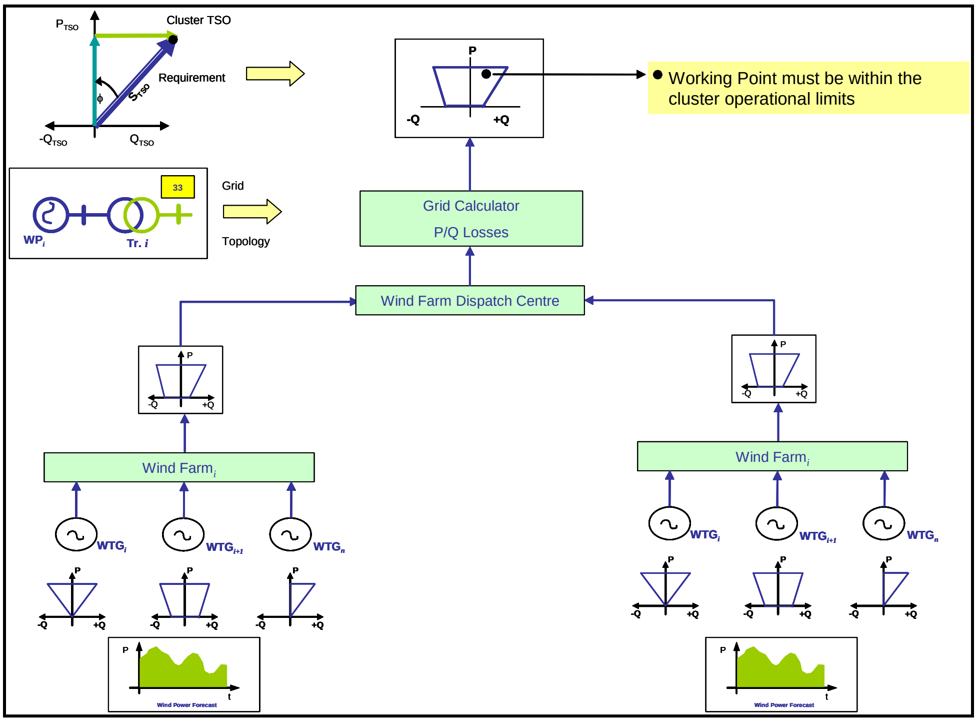

Figure 2: Layout of the P/Q capability calculation

3 DISPATCH CALCULATIONS

Once the requirement (set point) from the TSO is issued and it lies within the forecasted P/Q capabilities, it is a task of the WCMS to perform a dispatch calculation procedure. This procedure performs a dispatch of wind farms within the cluster to achieve the desired set point from grid operator. As it will be detailed in the following analysis; reactive power, power factor and voltage changes at the point of common coupling of the cluster are a function of the wind power feed-in and the power factor of the wind farms. This can be expressed by means of:

$$(Q, \cos\varphi, \Delta U, P)_{PCC} = f(P_{Wind}, \cos\varphi)_{Feed-In} \quad (1)$$

4 CONCLUSIONS

The already presented concepts of the WCMS and the further implementation of its control strategies will strongly support this wind energy development:

- The capability of integrating and controlling a large amount of wind power into the grid.
- The introduction of new control structures for the optimal control of wind energy.
- A general model that can be implemented in emerging wind power countries.

Future Power System Control Architecture

Kai Heussen[1)]

[1)] Technical University of Denmark, Denmark

ABSTRACT

This project looks at control of future electric power grids with a high proportion of wind power and a large number of decentralized power generation, consumption and storage units participating to form a reliable supply of electrical energy. The first objective is developing a method for assessment of control architecture of electric power systems with a means-ends perspective. Given this purpose-oriented understanding of a power system, the increasingly stochastic nature of this problem shall be addressed and approaches for robust, distributed control will be proposed and analyzed. The introduction of close-to-real-time markets is envisioned to enable fast distributed resource allocation while guaranteeing system stability. Electric vehicles will be studied as a means of distributed reversible energy storage with application to the case of the island Bornholm.

KEYWORDS

Power Systems, Control Architecture, Means-Ends Modelling, Functional Modelling

1 INTRODUCTION

An often stated quote from power system engineers is that the "the power system is the most complex interconnected system created by mankind". Variations of this statement have been used in context of explaining power system blackouts that often involve human failure, and it has been used to motivate increased funding for research, arguing for increased levels of automation. Though there may be some truth to that perspective, it is also a somewhat scary thought when it is used as an excuse to explain uncontrollable faults in the system.

Another statement often heard is that "the future power systems will be like the internet", thereby suggesting an analogy in which the internet's robust through decentralized control and its little need for central coordination is projected onto the electrical infrastructure. The internet is probably a larger complex system than any power system in number of participants – and yet it is so simple to use that everyone can actively participate.

These two statements are closely related as they both reveal a basic need of the human mind – the need for "understanding" the systems we are dealing with. In the first statement the term "complex system" is used to express that there is an issue with the complexity of the system. In some way it is too complex to be grasped by a human mind in its entirety. The

kh@elektro.dtu.dk

latter analogy expresses a need for simplification based on familiarities. However, the power system is its own kind complex system, with its own characteristics. The internet analogy may point out a hopeful direction, but the analogy does not hold when we look at details. Simply imposing another system's structure won't help reducing the complexity of the given system. What is needed instead is a close look at the principles of how power systems are organized today, and what the additional requirements in the future will be.

2 PURPOSE-ORIENTED MODELING OF CONTROL ARCHITECTURE

2.1 Functional Modelling

Any purposeful system created by humans can viewed from a means-ends perspective. This perspective starts with asking for the goals and functions:

- *Why* has this system been created, what goal did the creator want to achieve? What *purpose* did the creator have in mind?
- *What* does the system do to achieve this objective? Which *function* was used to serve the purpose?
- *How* have these function been implemented? Which *behaviours* and *structures* were used to create the functionality?

With these questions in mind, a functional model captures the intentionality of an engineered system, dissecting it in terms of abstraction levels from *goals* and *functions* further into *behaviours* and *structures*.

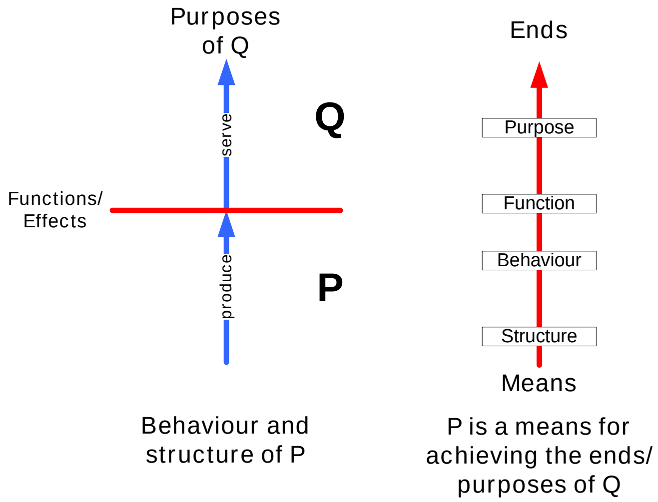

Figure 1: Mean-Ends in Functional Modelling [1]

Here, the lower levels correspond the more common modelling based on physical principles. Functional flows can be modelled in a modelling language called Multilevel-Flow-Modeling (MFM). It can capture mass-flow, energy-flow, and control functions and provides a framework for the integration of this multi-perspective, multi-level understanding of purposeful man-made systems [1].

2.2 On means and ends in Power Systems

The basic *objective* of a power grid is to enable the delivery electrical energy from electrical power sources to sinks. The *function* of the power grid is to serve as a medium for electrical AC energy. Considering the basic operating paradigms of a power system from a distance, this function is enabled by achieving two basic goals:

1) A stable (constant) frequency
2) Locally stable (constant) voltage levels

A further basic objective not included in the goals above is: keeping load flows within the limits of the power lines (this is related to currents). These are the most basic objectives of power system control functions. These functions can be classified into

a) protection systems
b) fundamental control loops
c) objective-based (coordinating) control (e.g. cost optimization), controller adaptation
d) coordination functions, including security checks, typical operator tasks
e) etc.

Analogous to the approach in [2] we can distinguish several levels of control, reaching from low-level automatic controls a), b) (Level 0), over more goal-oriented operation and optimization (Level I, c)), toward a more decision-making and planning oriented control functions (Levels II d), and Level III, high level tasks: long-term planning, “research”, …).

3 OUTLOOK

Following the approach illustrated in Section 2, a general functional architecture of power systems will be developed. This model can be used, for example, to define the purpose of and the requirements that should be met by a particular type of real-time market. It is expected that an integrative framework for current innovative structures, like Virtual Power Plants and MicroGrids will be found, and the control functionalities provided by modern converter-interfaced DER can be fitted into this framework. Further, the functional approach should be integrated with common modelling approaches for controller design such as behavioural modelling. All in all, this project is aimed at enabling operation of a power system with very high amounts of distributed generation and fluctuating renewable energies.

BIBLIOGRAPHY

[1] Lind, M. : The What, Why and How of Functional Modelling, ISSNP 2007

[2] Schweppe, F. C. : Power Systems 2000 hierarchical control strategies, IEEE Spectrum 1978

Direct Drive Generators for Future Wind Turbines

G. Shrestha, H. Polinder, J.A. Ferreira

Electrical Power Processing/ DUWIND, Delft University of Technology, Mekelweg 4, 2628CD, Delft, Netherlands, Phone: 0031-15-2782955, Fax: 0031-15-2782968

ABSTRACT

Direct drive generator can be reliable and near maintenance free due to the low number of moving part with relatively slow rotation. However they tend to be large and heavy for large wind turbines. The use of magnetic bearing could provide reduction of the weight of such direct drive generator. A comparison of a 5MW generator rotor design shows about 45% reduction in weight of the rotor.

KEYWORDS

Direct drive generator, magnetic bearings

1 INTRODUCTION

Direct drive generators used in wind turbines are large, heavy and expensive. Scaling them up will increase the size, weight and cost rapidly. This is mainly due to the mass of the structural material required. For large wind turbines, the maximum tip speed of the rotor blade is limited. Therefore the torque of the direct drive generator needs to increase for the same power level. There is a limitation on the maximum torque that can be produced in a given surface area. Therefore such direct drive machines tend to be built with a large radius to make them electromagnetically efficient. On first approximation the mass of active material increases quadratic to the increase in radius of the machine [2]. The structural material mass increases as a cubic function of the radius of the machine [4].

This paper presents a new concept for weight reduction of direct drive generator which is based on use of magnetic bearings. Then the design method is summarized and results of a 5MW design (analytical & FEM) are given and compared to a design using conventional method.

2 CONCEPT

The new concept of direct drive generator is based on the use of magnetic bearings to maintain the air gap between the stator and rotor of the large diameter machine. Such magnetic bearings can be used near the air gap of the machine and can be supported by the

g.shrestha@tudelft.nl

existing stator structure. Thus the heavy arms required to keep the rotor cylinder with a small airgap is removed. The new concept is shown in figure 1. All the wind loads are taken by the mechanical bearing. The rotor ring is a cylindrical ring made up of rectangular hollow cross section and stiffened using flat plates as shown in figure 2a. There magnetic bearing contains of 4 radial E core type actuators and 8 axial E core type actuators controlled in a differential mode. The torque carriers are made of I beams that carries the torque from the hub to the generator. The major loading is in the direction of rotation as other directional loading are compensated by the magnetic bearings.

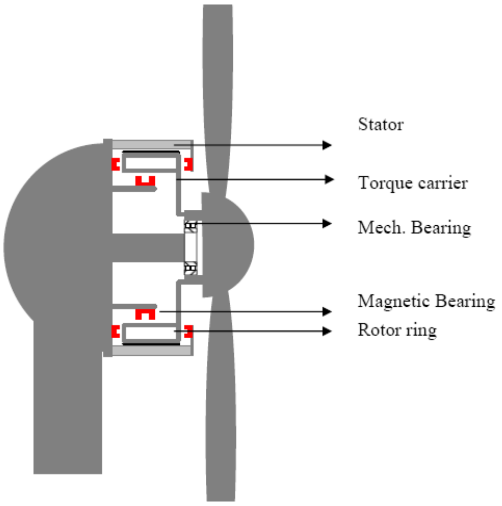

Figure 1: New concept of direct drive design

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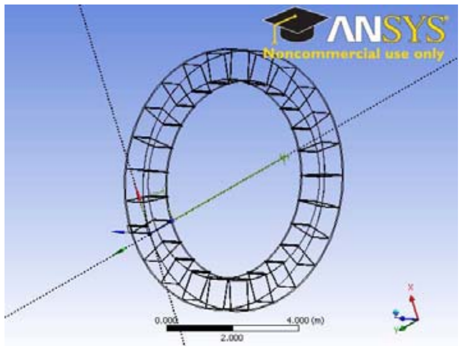

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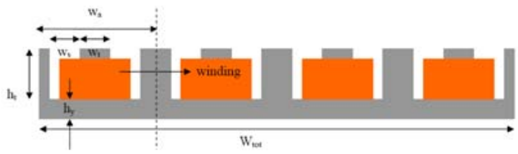

Figure 2: a. A hollow ring design, b. E core magnetic actuator

3 DESIGN METHOD AND RESULTS

A 5MW machine was designed. It is assumed that the stator structure does not change. The forces i.e the tangential, normal and the eccentric forces were calculated analytically. The structure of the rotor ring, torque carrier and magnetic actuator were analytically calculated to counteract such forces. Then Ansys FEM tool was used to verify the analytical results of the rotor ring and torque carrier. The ring design was also analysed for bending mode frequencies and kept above 40Hz. The results for a 5MW rotor are shown below in tables I-III.

Table I- Rotor Ring Parameters

Thickness of the section (t)	25mm
Height of section (l)	1m
Width of the section (w)	0.83
Ring stiffener	24
Total weight	20.5 ton

Table II- Torque carrier parameter

Arm type	**I Beam**
Length of flange	100 mm
Height of web	400 mm
Thickness of flange	30 mm
Thickness of web	20 mm
Mass of arm	292 kg
Total mass of 6 arms	1.75 tons

Table III- Magnetic actuator parameter

Parameters	Radial Actuator	Axial Actuator	Parameters	Radial Actuator	Axial Actuator
Airgap (nominal)	6 mm	6 mm	Length of actuator (arc)	939 mm	N/A
Design force F_{act}	300 kN	15 kN	Number of turns	100	100
Design Flux density	1.2 T	1.2 T	Resistance of the conductor	0.416 ohm	0.0266 ohm
Total surface area required	0.524 m^2	0.026 m^2	Weight of radial actuator (each actuator)	1.36 tons	71.4 kg
Ampere turn required (NI)	11.46kAT	11.46 kAT	Weight of all radial actuator	5.44 tons	571 kg
Current Density	3.3A/mm^2	3.3A/mm^2	Loss per actuator (Bias)	1.36 kW	0.087 kW
Copper area	5700mm^2	5700 mm^2	Total loss (Bias)	5.47 kW	0.7 kW
Fill factor	0.6	0.6	Loss per actuator (maximum at normal operating condition)	5.5 kW	0.350 kW
Height of tooth (h_t)	190 mm	190 mm	Maximum loss total	10.9 kW	1.4 kW
Height of yoke (h_y)	35 mm	35mm	**Worst case scenario (Starting)**		
Width of tooth (w_t)	70 mm	70 mm	Air gap	10mm	10mm
Width of the slot (w_s)	30 mm	30 mm	Flux density	1.7 T	1.7 T
Width of actuator (w_a)	200 mm	200 mm	Maximum force required	600kN	30kN
Total width (W_{tot})	800 mm	200 mm	Current density	7.8 A/mm^2	7.8 A/mm^2
Length of actuator (Straight)	935 mm	187mm	Ampere turn required	27 kAT	27kAT

4 CONCLUSIONS

The new concept of direct drive generator design is shown here. A design of 5MW generator rotor shows a weight of about 28 tonnes. The weight of a same size rotor using conventional design is shown to be about 50 tonnes [1]. Some other possibilities of design exists too for such magnetic bearing solution and has an encouraging scalability property. Therefore this can provide a solution for future wind turbine designs of larger power rating with less maintenance and still being cost effective.

ACKNOWLEDGEMENT

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BIBLIOGRAPHY

[1] McDonald A.S., Mueller M.A., Polinder H.: "*Comparison of generator topologies for direct drive wind turbines including structural mass*", ICEM06, Chania 2006

[2] H. Polinder and J. Morren, "*Developments in wind turbine generator systems*", Electrimacs 2005, Hammamet, Tunisia.

[3] Shrestha G., Polinder H., Bang D.J., Ferreira J.A.; "*Direct drive wind turbine generator with magnetic bearing*", EOW conference, Berlin 2007

[4] Mcdonald A.S., Mueller M.A., Polinder H.; " *Structural mass in direct drive permanent magnet electrical generator*", IET Renewable Power Generation, Vol.2, No. 1, pp 3-15, 2008

Sensor Design and Control Algorithm for Flaps on Wind Turbine Blades

Damien Castaignet[1)]

[1)] Vestas Wind Systems A/S, Aero-Systems, Denmark

ABSTRACT

Loads on wind turbines increase as the size of the rotor become larger and larger. Trailing Edge Flaps offer an alternative way of regulating these loads. The aeroelastic code Flex has been modified in order to simulate the aerodynamic behaviour of these flaps. By implementing the flap model in Flex, it will be possible to apply appropriate sensors and advanced controllers to the simulation of a wind turbine.

KEYWORDS

Trailing edge flap, Controls, Sensors

1 INTRODUCTION

The purpose of Trailing Edge Flaps is to reduce the design loads on the turbine rotor, nacelle and tower structure, in order to aim at a decrease in the cost of wind energy. Sensors and controllers are two important aspects of the flap system. Sensor design and advanced controllers are needed in order to get the maximum efficiency of the flaps.

2 IMPLEMENTATION OF THE TRAILING EDGE FLAPS IN FLEX CODE

2.1 Gaunaa-Andersen dynamic stall model

Flex is the code which will be used to run the aeroelastic simulations. The implementation of the Trailing Edge Flaps is based on the code written by P. B. Andersen and M. Gaunaa [1,2]. It is an extension of Theodorsen work [3] which includes a Beddoes-Leishmann type dynamic stall model. The dimensionless values C_L, C_D and C_M are calculated for each blade section and feeded into Flex.

2.2 Results

Simulations have been run with the two different cases:

- Using the Stig Øye dynamic stall model [4]
- Using the Gaunaa-Andersen dynamic stall model

daca@vestas.com

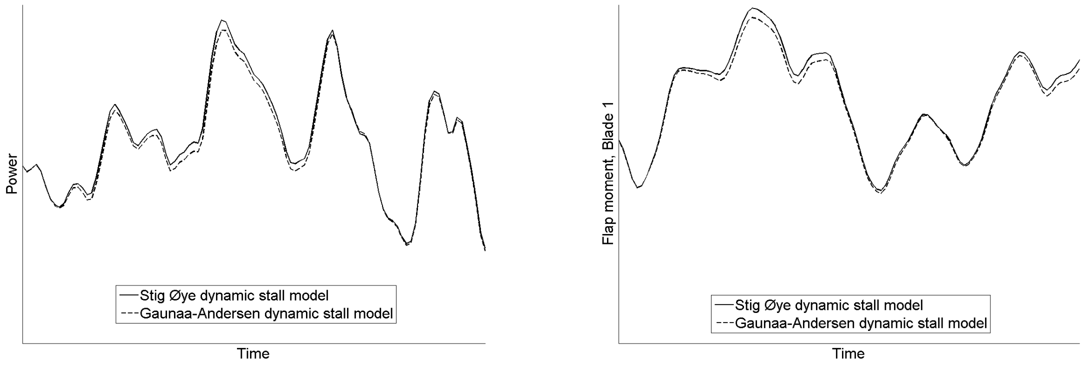

Figure 1: Produced power and blade root flap moment, simulated with the two different dynamic stall models.

These two dynamic stall models give similar results for both power and blade root flap moment (See Figure 1).

3 SENSOR DESIGN

Trailing Edge Flaps efficiency depends directly on the choice of the sensors that will be implemented on the wind turbine: type of sensors (accelerometers, strain gauges, pressure taps, pitot tubes, optic fibres…), location, and characteristics (accuracy, logging frequency…). An important parameter already studied by Peter Andersen is the time delay in response system [5].

4 DESIGN OF CONTROL ALGORITHMS

Controllers will be designed in order to reduce fatigue and ultimate loads for all the critical conditions a wind turbine can go through over the design life.

The advanced controllers will have to be fault tolerant: they need to handle distortion and damage of sensors and actuators. Predictive and self learning controllers will also be investigated.

5 CONCLUSIONS

This paper gives a short overview of the work that has to be done on sensors and controllers in order to use Trailing Edge Flaps in an efficient way.

BIBLIOGRAPHY

[1] Gaunaa, M., “Unsteady 2D Potential-flow Forces on a Thin Variable Geometry Airfoil Undergoing Arbitrary Motion”, Risø-R-1478, Risø, Denmark, June 2004.

[2] Andersen, P. B., Gaunaa, M., Bak, C., Hansen, M., H., "Implementing a Dynamic Stall Model for Airfoils with Deformable Trailing Edges", 46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2008-1328

[3] Theodorsen, T., "General Theory of Aerodynamical Instability and the Mechanism of Flutter", NACA Report 496, 1935.

[4] Øye, S., "Dynamic Stall simulated as time lag of separation", Department of Fluid Mechanics, Technical University of Denmark.

[5] Andersen, P. B., Gaunaa, M., Bak, C., Buhl, T., "3D Investigation of the Potential of using Adaptive Trailing Edge Geometry for Load Alleviation on Wind Turbine Blades", EWEC 2006, Athens.

Online Load Monitoring of Wind Turbines for Advanced Control and Optimized Operation

Ursula Smolka

Endowed Chair of Wind Energy at the Institute of Aircraft Design,

Universität Stuttgart, Germany

ABSTRACT

Wind turbines are equipped with a large number of operational sensors. But only few state-of-the-art sensor signals provide information about the present loading of the wind turbine. There is a lack of reliable and robust online load monitoring concepts that meet the demands of advanced control strategies, such as individual pitch control. These methods require additional local and continuous measurements. Thus sensors need to be examined with respect to their applicability for wind turbines and significance for the control variables of interest. The scope of this research covers signal post processing, redundancy setups and observer design. The final objective is to identify a system of sensors that provide reliable continuous data under real operational conditions. The evaluation will be based on numerical simulation and on field testing as well.

KEYWORDS

load monitoring, reliable measurement, observer, fatigue reduction, operational control

1 INTRODUCTION

Conventional wind turbines are equipped with a large number of operational sensors. But only few sensor signals, such as rotor speed and nacelle acceleration, provide information about the actual loading of the wind turbine. With respect to advanced control strategies, e.g. based on individual pitch action, their significance and applicability is limited as these methods require local measurements which typically record the blade root bending moments or tower bottom tilt and yaw moments continuously.

As part of an ideal load monitoring concept sensors should capture the various locally distributed loads which trigger alerts even before damages are developing. This is to be combined with a continuously stable load reducing control strategy that facilitates optimized energy yield in relation to the accumulated load history of the turbine.

Ursula.Smolka@ifb.uni-stuttgart.de

On a more detailed level, the sensors employed in such a system have to endure a high number of load cycles and material stresses where conventional sensors such as electrical strain gages fail [1]. On the other hand promising solutions such as inflow measurements with pitot tubes [2], ultrasonic strain measurements [1] and optical strain gages [3] are still subject of ongoing development. Hereby reliability and robustness of the measurements is a major concern.

Further on, the control variables of interest might not always be directly measurable. So the sensor placement and the signal analysis play an important role in providing local loading measurements with relevance to the control objective of the whole turbine.

2 RESEARCH OBJECTIVE

The research objective is to identify and employ a load monitoring concept that meets the demands of advanced control strategies requiring reliable, robust and continuous measurements. Several sensors with respect to their applicability will be examined. In accordance with suggested control algorithms in literature, relevant control variables for fatigue load reduction will be identified.

This is followed by a detailed elaboration of a load monitoring concept that explores the possibilities to combine signals of various sources and is capable to deduce quantities of interest. To employ both model-based estimations and direct measurements seems promising. The feasibility of the suggested load monitoring concept with respect to real-time processing and noise suppression will be demonstrated with reference to data from field testing.

This paves the way for redesigning well established control objectives with respect to both dynamic control and operational control. While the results of a reliable load monitoring system will be beneficial for advanced concepts like individual pitch control as well, this research anticipates to show the relevance of load monitoring signals for the operational control of the wind turbine. By this, improved operational control will facilitate optimization of the energy yield and operational costs. Eventually it is targeted to demonstrate the results on a dynamic wind turbine model and a test turbine.

3 CONCLUSIONS

This paper briefly motivates the need of online load monitoring concepts. The focus mainly lies on the application of sensors suitable for wind turbines and the subsequent evaluation and analysis of the signals obtained. This part of the research is carried out in cooperation with an industry partner aiming to design advanced control techniques for load reduction on wind turbines.

The performance and the benefits of the proposed load monitoring concept will be evaluated in numerical simulations and field testing as well.

BIBLIOGRAPHY

[1] Geyler M, Caselitz, P, Giebhardt, J. Lastreduzierende Pitchregelung für Windenergieanlagen. *Erneuerbare Energien 2007* ; **9:** 54 -58.

[2] Larsen TJ, Madsen HA, Thomsen K. Active load reduction using individual pitch, based on local blade flow measurements. *Wind Energy 2004*; **8 :** 67-80.

[3] Marsh G. Intelligent blade monitoring – the benefits. *Renewable Energy Focus 2008*; **1:** 50-55.

Coordinated Frequency Control of Wind Turbines in Power Systems with High Wind Power Penetration

Germán Claudio Tarnowski[1], Jacob Østergaard[1]

[1] Centre for Electric Technology-DTU, Denmark

ABSTRACT

In new Power Systems (PS) architectures with intentional islanding of distribution grids and high Wind Power (WP) penetration frequency control becomes a difficult task. Active power/frequency control brings a new vision in WP operation: wind farms operation becomes much more flexible and similar to conventional power plants. This paper addresses the behaviour of a wind farm active power output through computational simulation implementing an active power control methodology. It is shown a capability of modern wind power system for fast modulation of the injected active power into the grid if a suitable output derating factor is applied. Discussions on how the wind turbine active power output should be in island operation and how wind power generation can be coordinated in order to contribute to the frequency stability are addressed. This paper is related to a PhD project aimed at developing a control scheme for wind turbine frequency control and PS island operation support by real-time balancing the wind turbine power production, in order to integrate an increased share of wind power in a PS.

KEYWORDS

Wind power, variable speed, frequency control, islanded operation

1 INTRODUCTION

The penetration level of Wind Power Generation (WPG) is increasing rapidly at Medium Voltage and High Voltage levels, bringing a wide range of technical issues. In PS with high penetration level of WPG, or intentional islanding of distribution systems, frequency control becomes a very difficult issue. In order to maintain the PS planning and secure operation with large scale of WPG, Grid Codes (GC) are being updated demanding more flexibility and control capability from Wind Turbines (WT) and Wind Farms (WF) [1]. Although GC differs from one PS to another, some updates in GC concerns with the low-voltage-ride-through capability of WT and requirements of reactive power support. Nevertheless, frequency control capability and active power regulation for frequency stability will be the next step in

gct@elektro.dtu.dk

WT/WF technology development for matching high levels of wind power penetration. Ancillary services, rendered to maintain voltage and frequency stability through control of active and reactive power, are normally supplied from the large dispatched power plants, but alternatives are required as the production share of these plants is decreasing giving place to fluctuating power sources. In order to reach high levels of wind power penetration, wind power systems should also be able to supply ancillary services. The WF must be able to produce more or less active power in order to compensate for a deviant behaviour in the frequency measured at the WT terminals or at the WF Point of Common Coupling (PCC) [2]. Therefore WT/WF must fulfil requirements similar to that applied to conventional power plants. This work deals with the study and development of frequency control methods for increasing a high level of WPG in PS taking advantage of the controllability of Variable Speed Wind Turbines (VSWT). The interest is focused on frequency stability problems in weak/islanded distribution systems with large share of WPG, as is the case of the Danish island of Bornholm, which has been turned into a full-scale lab for studies of future power systems with high wind power penetration by Technical University of Denmark. As a starting point, this paper presents simulation results of a WF composed of VSWT-Doubly Fed Induction Generators (DFIG) where is applied an active power regulation scheme [3], with the objective to see the capability of the WF for producing different levels of active power and for contributing with active power injection from inertia response. As frequency control is a dynamic action of generating systems (and loads) it is important to know and understand what are the capabilities of WT/WF for that dynamic action in order to go further into studies and solutions for frequency control with wind power systems. Problems generated during islanded/weak grid situations with high wind power penetration are of special interest. Comments on WT/WF operational policy in islanded/weak distribution systems are addressed in the paper.

2 WIND FARM ACTIVE POWER REGULATION AND INERTIA RESPONSE

2.1 Active power regulation in wind farms with VSWT

An active power regulation scheme for wind farms with VSWT-DFIG is shown in Figure 1 where a simplified wind farm with three 3.6 MW Wind Turbines was implemented. Details about WT and WF modeling, control and parameters used in this paper can be found in [3]. Let P_{parq} denote the total active power delivered to the grid at the PCC and P_{a1}, P_{a2}, P_{a3} denote the generated active power from each generator in the WF. Each VSWT-DFIG is provided with individual active and reactive power regulation scheme through rotor side converter, and rotational speed limitation by acting on pitch angle [3]. A WF central controller (a simple PI controller in this case) compares the WF set point P^*_{parq} with the total active power production, P_{parq}, and generates a control signal P_{com} which is sent to all WT in the

WF. Each VSWT-DFIG receives the wind farm P_{com} signal as shown in Figure 1. The global reference for the active power of the WF, P^*_{parq}, is established according to some specific policy, e.g. available wind power forecast for the WF; policies of the PS operator; WF Output Derating Factor (ODF) for frequency control capability; etc.

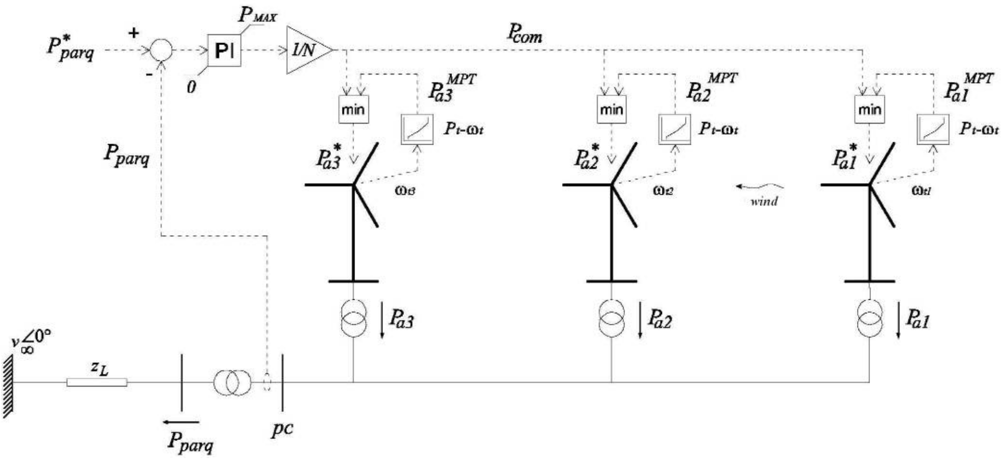

Figure 1: Wind Farm with Active Power Regulation

2.2 Active power performance with variable reference input

One characteristic of the implemented WT/WF control scheme is to allow the WT to rotate at a higher speed when the active power reference is decreased, increasing in this way the stored kinetic energy in the wind turbine rotors. The WF active power output can remain regulated while the wind speed variations are filtered through rotational speed variations and pitch angle actuation, always keeping the operational point as near of the optimum aerodynamic point as necessary [3]. In this paper the WT/WF capability for active power injection is assessed by applying a variation in the active power reference in a short period of time. Two simulations of 60 seconds were carried out under the same wind speed conditions. Initially in both simulations the WF active power output was approximately 0.4 *pu*, which is 70% of the available wind power in the plant (ODF) at the simulated period. From this point, relatively high and fast variations of the active power reference was applied to P^*_{parq}. First simulation results are shown in Figure 2 where time behavior of relevant variables, such as reference and total WF production; individual WT active power production; rotational speed and pitch angles can be seen. From this figure one can see how the WF production nicely tracked the P^*_{parq} reference at the beginning of the variation (ramping up), injecting into the grid active power coming from both rotors kinetic energy and available wind power. It is possible to see a peak (0.8 pu) of active power injection coming from rotating masses when a high and fast variation in the WF set point was applied. As the new WF set point was higher than the available wind power, the WTs rotational speed fastly decreased to optimum values, going the WF automatically to operate according the optimum production (~0.55 pu) (maximum power tracking). Ramping down the P^*_{parq} set point below a suitable value it was possible to regulate the WF output production, increasing the WT rotational speed but limiting it by pitching the blades.

For the second simulation, the P^*_{parq} reference profile is shown in Figure 3 together with the relevant variables of the system. It can be seen that, for the simulated case, it was possible to increase P_{parq} output up to 110% (0.6 pu) of the available wind power holding this value for approximately 3 seconds before the WT rotational speed decreased to values that could not permit to inject active power from kinetic energy. The P^*_{parq} reference was after decreased to 70% for permitting the WT to increase the rotational speed. The WF reference ramping up to 110% and down to 70% was repeated a second time. In the last P^*_{parq} ramping up, the WF production was the available wind power (maximum power tracking).

From the simulated case, it can be seen that the WF output nicely tracks the active power reference input P^*_{parq} whenever there is enough kinetic energy and available wind power, showing the ability for fairly fast active power transitions. Since the generated power and the wind turbine rotational speed are independently controlled, a slow dynamics in the blade angle control loop does not compromise the fast dynamic of active power regulation.

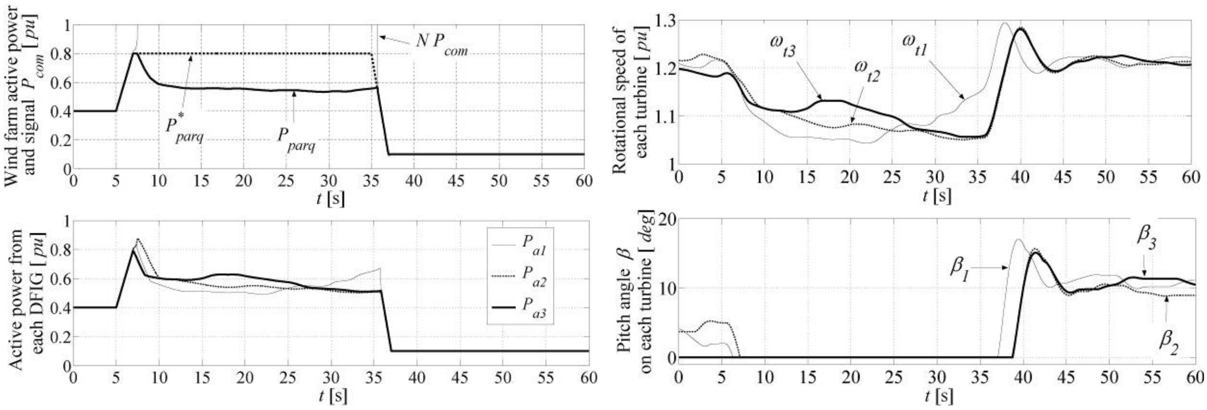

Figure 2: First WF simulation

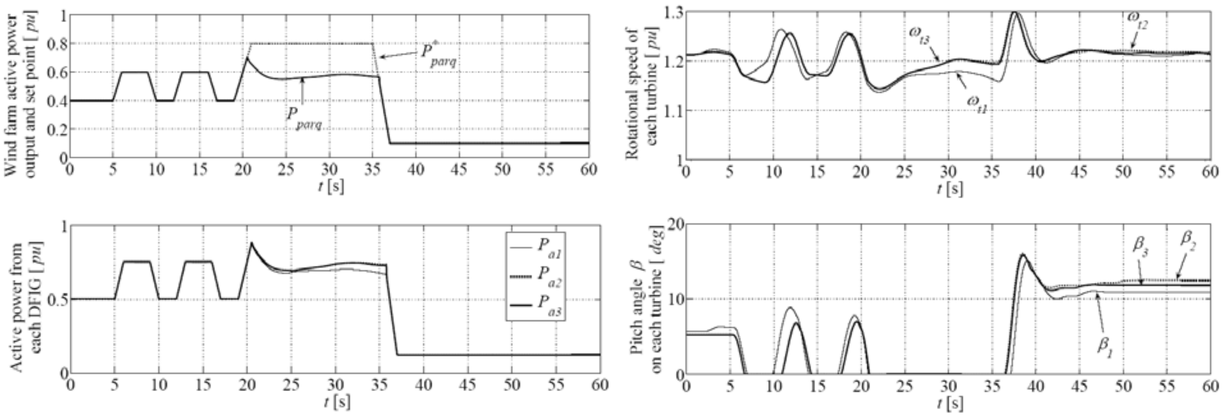

Figure 3: Second WF simulation

3 ACTIVE POWER OUTPUT OF MODERN WIND POWER SYSTEMS

Normally, grid operators continuously dispatch sufficient conventional generation to match the demand, plus levels of Reserve and Primary Frequency Response (PFR) capability to cover loss of generation or changes of demand. This frequency service is automatic and continuous. If ancillary services are supplied solely by few central stations, then large wind power variations also require to be compensated by these central stations supplying the ancillary services. In order to reduce the requirements of the central stations (and the operation costs), modern wind power systems must also be able to supply ancillary services. This is possible of course when the wind blows.

From the previous simulations it can be seen that modern wind power system has a capability for fast modulation of the injected active power into the grid if a suitable ODF is applied. These simulation results permit to go further with ideas of studying and implementing frequency control schemes in wind power systems. Assuming that the wind power penetration level is relatively high, a coordinated frequency control scheme would present several advantages especially during islanded or weak grid situations, as is the case of Bornholm Island power system [5, 6]. The coordinated frequency control scheme should operate automatically when the WF is connected to strong or weak/islanded electrical grids and permit optimal power production when operating in grid-connected mode. In grid-connected mode, VSWT active power is normally maximized in contrast to the weak/islanded system mode of operation, where the power balance between VSWT production and load demand should be aimed. In weak/islanded systems, the control system of VSWT should continuously adjust the output active power and the frequency close to the nominal value. It is difficult to compensate a system frequency reduction followed by a loss of generation using wind power, as this compensation normally requires the PFR to react within 0-10 seconds and be sustained for a further 20 seconds or more [4]. It would be necessary to operate the VSWT with an ODF that considers such a probable loss of generation, being it equivalent to a “wind power reserve”.

Due the low capacity of VSWT for active power reserve, a coordinated frequency control scheme should be intended as collaboration of WT with the other types of generators presented on the weak/islanded grid in order to compensate fast active power (frequency) fluctuations in the system due to load changes or wind power fluctuations. For achieving such collaboration it might be necessary to study and define a suitable active power response (output profile) from wind farms when a change in the system frequency is detected. That active power response should match the technical capabilities and limitations of WT as well as the necessary active power injection that would make possible a stable and well operated weak/islanded system. Probably a good choice for a WT/WF frequency control system could be implementing a kind of combination between VSWT inertia response control loops and PFR systems. A more deep assessment of VSWT frequency response characteristic depending on its loading level is necessary as well as a comparison with conventional synchronous generators. Models and strategies for fast frequency control during island operation has to be derived, and simulation results of a weak/islanded electrical network supplied by VSWT has to be performed. In this work, Bornholm Island power system will be used for conducting studies of weak/islanded interconnected network with significant wind power penetration, and development of control systems.

4 CONCLUSIONS

If ancillary services are supplied solely by few central stations, then large wind power variations also require to be compensated by those central stations. Wind turbines with power converters are able to flexibly control its active and reactive power output using the converter controller. Simulation results of an implemented wind farm active power control methodology show that modern wind power systems have a capability for fast modulation of the injected active power into the grid if a suitable output derating factor is applied. This control scheme can be adapted to provide frequency support by real-time balancing the wind turbine power production. According to simulations, the active power injection from inertia response can be around 140% of available wind power for a short time. It is expected that by derating the wind farm output it is possible to increase the frequency control capability of wind systems. Further research of wind turbine inertia influence; acceptable level of wind turbine deceleration; power system frequency recovery dynamics; different frequency control loops schemes; etc., must be conducted in order to fully assess the frequency support capability of wind turbines under different wind speed conditions.

BIBLIOGRAPHY

[1] Iov, F.; et al: A Survey of Interconnection Requirements for Wind Power. Proceedings of Nordic Wind Power Conference, NWPC 2007. Risø-DTU, Denmark, 1-2 Nov. 2007.

[2] Hansen, A. D. ; et. al. : Centralised power control of wind farm with doubly fed induction generators. Elsevier. Renewable Energy 31 (2006) 935-951.

[3] Tarnowski, G. C. and Reginatto, R. : Adding Active Power Regulation to Wind Farms with Variable Speed Induction Generators. IEEE PES General Meeting, 2007. pp 1-8. 24-28 June 2007.

[4] Erinmez, I. A. ; et. al. : NGC Experience with Frequency Control in Englnd and Wales – Provision of Frequency Response by Generators. IEEE PES Winter Meeting, 1999. pp 590-596. Vol. 1. 31 Jan-4 Feb 1999.

[5] Chen, Y. ; Xu, Z. ; Østergaard, J. : Frequency Analysis for Planned Islanding Operation in the Danish Distribution System – Bornholm. Submited to the 43rd International Universities Power Engineering Conference, UPEC 2008. Padova, Italy, 1-4 Sep. 2008.

[6] www.dtu.dk/centre/cet.aspx

Promising Direct-Drive Generator for Large Wind turbines

Deok-je Bang, Henk Polinder, Jan Abraham Ferreira

Electrical Power Processing / DUWIND / Delft University of Technology, The Netherlands

ABSTRACT

This paper discusses promising direct-drive generator concept for large wind turbines. Different permanent magnet (PM) machines such as the radial flux (RF), the axial flux (AF), and the transverse flux (TF) PM machines are investigated to find a suitable machine type for direct-drive. Some promising solutions for large direct-drive are proposed in electromagnetic design, structural design and practical issues.

KEYWORDS

Direct-drive, Generator, Permanent Magnet, Axial Flux, Radial Flux, Transverse Flux

1 INTRODUCTION

Direct-drive wind turbines have been built to increase the energy yield, to reduce gearbox failures, and to lower maintenance problems [1][2]. A noticeable trend on the wind turbine market is scaling up the size of the turbine. It is also a trend that the location to install wind turbines is moving to offshore. Therefore more simple, robust and reliable generator systems with high performance and low cost are required for (large offshore) wind turbines. The direct-drive generators are thus attractive in terms of energy yield, reliability, and maintenance problem. Direct-drive generators operate at low speed, thus high torque is demanded. High torque demands high tangential force and large air gap diameter of the generator. When scaling up the wind turbine, this phenomenon grows more and more. This result is thus that the direct-drive generator is large and heavy. There are still different opinions about what is the most suitable generator system among existing wind turbine technologies such as direct-drive and geared generator concepts.

The generator system with the maximum energy yield and the minimum cost can be defined as the most suitable generator system as stated earlier. For maximizing the energy yield, the direct-drive PM generator system is better than both the geared generator system and the direct-drive electrically excited (EE) generator system. For minimizing the system cost, material reduction is required. Therefore different PM machines such as the RF, the AF and the TF PM machines are investigated to find a suitable machine type for direct-drive. Some promising solutions for large direct-drive are proposed.

d.j.bang@tudelft.nl

2 PM MACHINES FOR DIRECT-DRIVE

The PM machines have strengths such as higher power to mass ratio, higher efficiency, higher reliability and higher energy yield than the EE machines. Therefore PM machines are selected as promising machines for direct-drive wind turbines. In this paper, the features of three different PM machines such as the RFPM machine, the AFPM machine and the TFPM machine are investigated and discussed to find the most suitable machine type for direct-drive.

2.1 RFPM machine

The RFPM machine is producing magnetic flux in the radial direction with PMs which are radially oriented. Most of the RFPM machines have a conventional inner rotor design, but some outer rotor designs have also been presented in literature. Figure 1 depicts a RF machine with surface mounted PMs and a linear cross section of two poles. When using PMs for the direct-drive generators, the generators can operate with good and reliable performance over a wide range of speeds. In manufacture, the simple way of constructing the machine with high number of poles is gluing PMs on the rotor surface. RF machines are structurally stable and widely used. Most of the low speed megawatts wind generators are RF machines on the market. Thus RFPM machines seem to be the most interested machine type for large scale direct-drive wind turbines. However, a lot of work has been done on optimizing the electromagnetic design of RFPM machines. Therefore it seems hard to reduce the active material mass and cost of RFPM machines significantly.

2.2 AFPM machine

The AFPM machine is a machine producing magnetic flux in the axial direction with PMs. AFPM machines can be classified into slotted machines and slotless machines. Figure 2 depicts a slotted AFPM machine. An AFPM machine has the following strengths compared to RFPM machine.

- simple winding (in a slotless machine)
- low cogging torque and noise (in a slotless machine)
- short axial length
- higher torque/volume ratio

However, the following drawbacks of AFPM machines compared to RFPM machines have been also discussed.

- lower torque/mass ratio
- larger outer diameter and large amount of PM (in a slotless machine)
- structural instability

- difficulty to maintain air gap in large diameter (in a slotted machine)
- difficult production of stator core (in a slotted machine)

In order to apply AFPM machines in large direct-drive wind turbines, these drawbacks must be overcome since they cause cost increase and difficult manufacture.

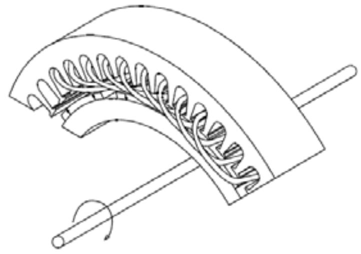

Figure 1: Surface mounted RFPM machine

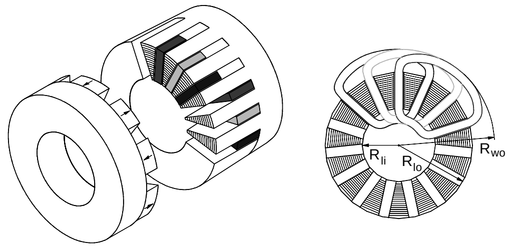

Figure 2: Slotted AFPM machine [3]

2.3 TFPM machine

The transverse flux (TF) principle means that the path of the magnetic flux is perpendicular to the direction of the rotor rotation. The major difference of TFPM machine compared to RFPM and AFPM machines is that TFPM machine allows an increase in the space for the windings without decreasing the available space for the main flux. TFPM machine can also be made with a very small pole pitch compared with the other types. This feature results in higher induced voltage as shown in (1).

$$e_{\max} = N \cdot \phi_{\max} \cdot 2\pi \cdot f = N \cdot \phi_{\max} \cdot 2\pi \cdot \frac{v_g}{2\tau_p} \quad (1)$$

Where, N is the number of winding turn, $\phi_{\max}$ is the maximum flux linking the stator winding, f is the frequency, v_g is the moving speed and τ_p is the pole pitch.

Figure 3 depicts a TFPM machine which is a flux concentrating single-sided type.

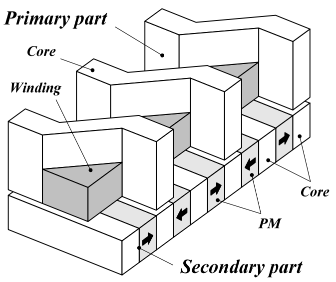

Figure 3: Flux concentrating single-sided TFPM machine

The strengths of TFPM machines compared to RFPM and AFPM machines can be summarized as follows:

- higher force density
- considerably lower copper losses
- simple winding

Contrary to the strengths, the construction of TFPM machine is more complicated than RFPM and AFPM machines, since TFPM machine has a three dimensional flux path. A TFPM machine with a large air gap seems not to be attractive because its cost advantage is similar or even low compared to RFPM machines [3]. These drawbacks make the TFPM machine more unattractive for large direct-drive applications. However in a number of references, various topologies of TFPM machine have been proposed to overcome the drawbacks. Each topology proposed in the references has one strength at least to make the TFPM machine attractive. If it is possible to overcome the drawbacks by a new topology adopting and combining the strengths of different topologies, the TFPM machine will be attractive for large direct-drive wind turbines.

3 PROMISING DIRECT-DRIVE GENERATOR CONCEPTS

The generator system with maximum energy yield and minimum cost can be defined as the most suitable generator system for wind turbines. To achieve that, the optimization of generator system is required in the electromagnetic and mechanical design. As stated above, the direct-drive PM generator system has the highest performance and reliability compared to both the geared generator system and the direct-drive electrically excited generator system. Considering only the energy yield, the direct-drive PM generator system can be the most suitable system. However, the direct-drive generator system has drawbacks such as large size, large mass and high cost. Therefore some promising solutions for the most suitable direct-drive generator system are proposed considering the electromagnetic part, the structural part and the practical issues.

3.1 Electromagnetic design

In order to make the electromagnetic part the most suitable, the mass and cost minimization and the output power maximization are required. Therefore followings are proposed as promising solutions.

- Plural module concept with short flux path results in material reduction by decreasing slot pitch and height without increasing leakage flux as shown in Figure 4.
  RFPM and AFPM machines are limited to use this plural module concept, since the pole pitch is decreased and the leakage flux is consequently increased, when decreasing the slot pitch to make the magnetic flux path short. However the TFPM machine is a potential configuration to use the plural module concept, because the pole pitch is not decreased, when decreasing the slot pitch.
- An increased iron core area can produce a higher induced voltage as shown in (2). Figure 5 depicts two promising concepts to increase the core area. The concepts have been proposed by Mecrow, Weh and Maddison *et al* [3].

$$e_{\max} = N \cdot B_{\max.core} \cdot A_{core} \cdot 2\pi \cdot f \qquad (2)$$

Where, $B_{\max.core}$ is the flux density in the iron core and A_{core} is the iron core area for the flux linkage.

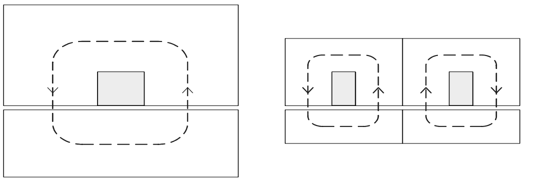

Figure 4: Concept to reduce active material

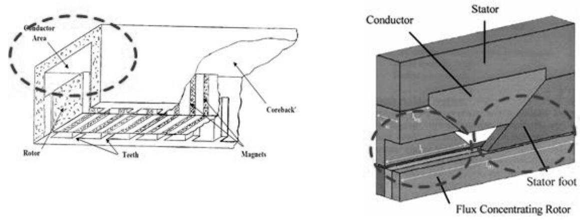

Figure 5: Concepts to increase the iron core area [3]

3.2 Structural design

The duty of the structural part can be defined as maintaining the air gap and taking the rotational force from the rotor blades. Traditional large direct-drive concepts have used heavy and strong structures and mechanical bearings. These traditional concepts make the direct-drive generator system more unattractive for large wind turbine applications. If it is possible to perform the duty of the inactive part by a new concept with the minimum mass and cost, then the inactive part can be the most suitable. Some promising solutions are proposed as follows.

- A machine with very lightweight mechanical structure
- A machine with additional magnetic bearing
- A machine combined with magnetic bearing which can control the air gap

3.3 Practical issues

Considering the production, transportation, installation, operation and maintenance of the generator system, following generator constructions are proposed as promising solutions for large direct-drive wind turbines.

- A modular construction that can be easily assembled, separated, transported and installed.
- A modular construction of which each module can work individually: That means the generator can continue to produce electricity, if a few parts fail.
- A construction with flexible and very lightweight joint instead of heavy and stiff main shaft - to take the rotational force from the rotor blades to the generator

4 CONCLUSIONS

Different promising machines such as RFPM, AFPM and TFPM machines have been investigated to find a suitable PM generator type for direct-drive. In order to minimize the electromagnetic material, an electromagnetic configuration with shorter flux path is required. The TFPM machine is a potential configuration to have short flux path than the RFPM and AFPM machine. Some promising solutions on the structural design and practical design are also proposed.

BIBLIOGRAPHY

[1] H. Polinder, F.F.A. van der Pijl, G.J. de Vilder, P. Tavner, “Comparison of direct-drive and geared generator concepts for wind turbines”, IEEE Trans. Energy Conversion, Vol. 21, pp. 725-733, September 2006.

[2] A.S. McDonald, M.A. Mueller and H. Polinder, “Comparison of generator topologies for direct-drive wind turbines including structural mass”, in Proc. of the International Conference on Electrical Machines(ICEM), pp. 360.1-7, September 2006.

[3] M. Dubois, “Optimized permanent magnet generator topologies for direct drive wind turbines”, Ph.D. dissertation, Delft University of Technology, Delft, The Netherlands, 2004.

Wind Turbine Condition Monitoring and Fault Diagnosis using Wavelet Transforms

Wenxian Yang[1], Peter J. Tavner[1]

[1] New & Renewable Energy Group, School of Engineering, Durham University, Durham DH1 3LE, United Kingdom

ABSTRACT

Some large wind turbines use a synchronous generator directly-coupled to the turbine. This paper considers condition monitoring and diagnosis of mechanical and electrical faults in such a variable speed machine. The application of wavelet transforms is investigated because of the disadvantages of conventional spectral techniques in processing instantaneous turbine signals. In this paper a new condition monitoring technique is proposed which removes the negative influence of variable wind in machine condition monitoring. The diagnosis of rotor imbalance in the wind turbine will be done, heralding the detection of wind turbine electromechanical faults by power analysis.

KEYWORDS

Synchronous generator, wind turbine, condition monitoring, fault diagnosis, wavelet transforms.

1 INTRODUCTION

With advances in wind turbine technology and government decisions that are favourable to 'green' or renewable power, wind turbines are becoming an increasingly economically viable alternative to conventional fossil-fuelled power generation. In some countries, notably Germany and Denmark they have been playing a vital role in the power network [1], although not without some problems. However, wind turbines because of their variable load condition and aggressive operating environment, wind turbines can be subject to relatively high failure rates, although they are beginning to show a reliability that is better than some other forms of power generation, for example diesel generators [2]. So developing economic condition monitoring and fault diagnosis techniques for them would be highly desirable. SCADA techniques are being applied very widely to wind turbines but the data rate, once every 5-10 mins, is too slow for most rotating machine fault diagnosis. There are many condition monitoring techniques developed in electric power production, aerospace, marine propulsion, and other process industries which could be applied to wind turbines but the results have not

Wenxian.yang@durham.ac.uk

proved satisfactory to date due to the peculiarities of the wind turbine, that is slow and variable speed, at least for the larger types. In recent years, some efforts have been made to improve this situation [3]. However, the majority of wind turbine condition monitoring and fault diagnosis techniques proposed [4, 5] have used Fourier Transform (FT) techniques, which are less capable of solving the problem due to its shortcomings dealing with non-stationary signals. In view of this, in this paper the potential application of the wavelet transform to the condition monitoring and fault diagnosis of wind turbines is investigated. This paper carries forward the previous work described in [6]. The Discrete Wavelet Transform (DWT) is used for noise cancellation as the signals from the wind turbine contain noise which is difficult to remove by using a conventional filter with fixed cut-off frequencies. The Continuous Wavelet Transform (CWT) is used for feature extraction purpose. A new technique, inspired by the torque-speed data obtained from a series of load and no-load experiments on a wind turbine, is proposed for assessing the running condition of the wind turbine. The effectiveness of the technique is validated by the detection of generator winding and rotor imbalance faults on the test rig. Experimental results show that the application of the DWT dramatically enhances the viability of this technique for wind turbines. In order to further simplify and reduce the cost of wind turbine condition monitoring and fault diagnosis, the possibility of detecting wind turbine mechanical faults by analysis of the power signal is also investigated. The CWT plays a vital role in extracting faulty features from the power signal.

2 TEST RIG FOR SYNCHRONOUS GENERATOR WIND TURBINES

In order to simulate the effects of wind turbines working under different conditions and develop the new condition monitoring and fault diagnosis techniques, a wind turbine test rig was built, as shown in Fig.1.

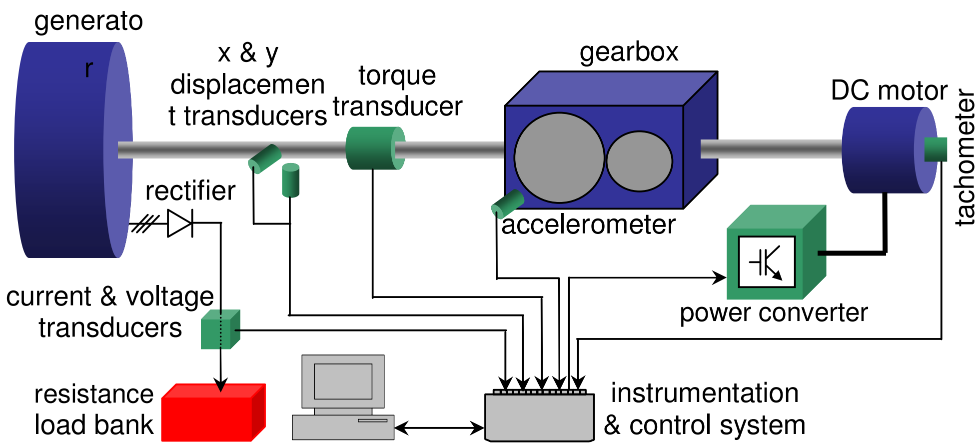

Figure 1: Wind turbine test rig and the transducers fitted to it

The test rig comprises a 50kW DC variable speed drive controlled motor, a two-stage gearbox and a three-phase synchronous permanent-magnet generator. The generator has

84 coils on the stator, 108 permanent-magnets on the rotor and each coil was rectified, then coupled to a DC bus and fed to a resistance load bank.

The test rig is controlled by LabVIEW so that a variety of wind speed inputs can be applied and the relevant signals can be collected from the drive train and terminals of the generator. As shown in Fig.1, a number of transducers are fitted to the rig to measure the shaft rotational speed, torque and vibration. The load DC current and voltage are measured at the terminals of the generator with the aid of data acquisition equipment installed in control cabinet of the test rig. In the experiments, the speed of the DC motor is controlled by an external model, in which both the properties of natural wind and the mechanical behaviour of turbine rotor are incorporated. In the investigations, both generator electrical and wind turbine mechanical faults were simulated on the test rig as follows:

- A generator stator winding fault was simulated by simultaneously shorting the load bank to ground;
- A full short circuit fault was simulated by connecting one of the phase terminals of the generator and resistance bank to ground;
- A rotor imbalance fault was simulated by attaching a mass to the outer surface of the generator rotor.
- A drive train mechanical fault was simulated by an eccentricity fault in the test rig gearbox.

The diagram of the test rig gearbox is shown in Fig.2, from which the gear ratio can be easily obtained, i.e.

$$r_g = \frac{\omega_r}{\omega_s} = \frac{Z_2}{Z_1} \cdot \frac{Z_4}{Z_3} = \frac{79}{36} \cdot \frac{66}{13} = 11.14 \tag{1}$$

where ω_r represents the rotational speed of the DC motor, ω_s stands for the rotational speed of the synchronous generator, and Z_i (i=1~4) indicate the tooth numbers of the gears.

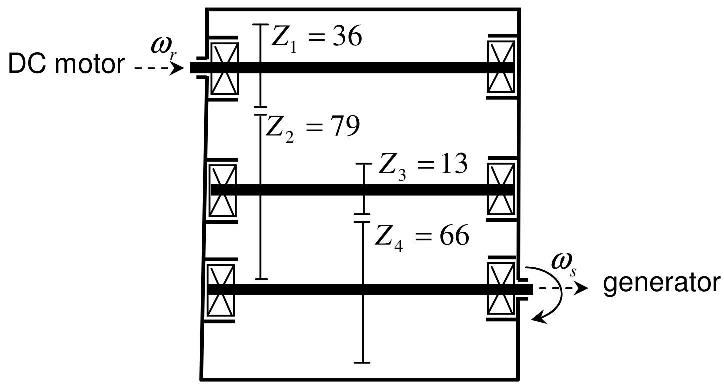

Figure 2: Diagram of the gearbox used in the test rig

3 CONDITION MONITORING TECHNIQUE

In order to develop an effective technique for monitoring the running condition of synchronous generator wind turbines, a series of full and half load tests were conducted on the test rig. Different loads and fault conditions were applied to the rig during the experiments. The shaft torque and rotational speed data measured in the different cases are plotted in Fig.3. The polynomial equations fitting to these data are also derived with the aid of the polynomial curve fitting technique [7]. In Fig.3, the fitting curves and the corresponding polynomial equations are given as well for facilitating analysis.

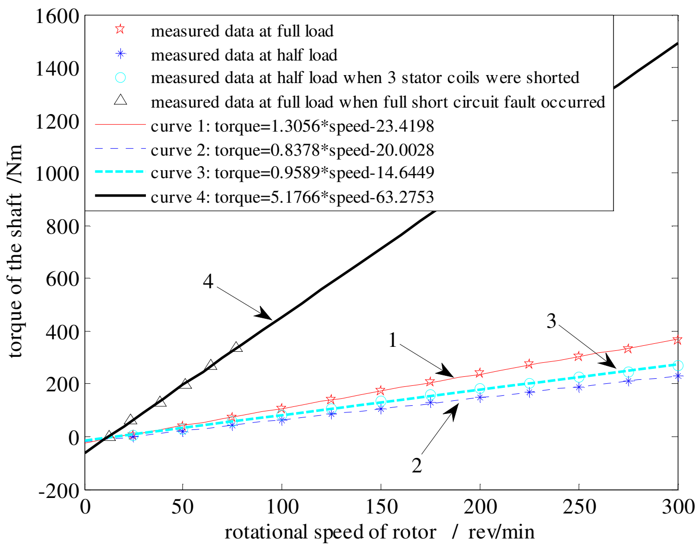

Figure 3: The shaft torque and speed data measured in the full and half load tests

From Fig.3, it can be seen that the generator exhibits different torque-speed characteristics under different load and fault conditions. Most interestingly, the generator shows a significant change in torque-speed characteristic when faults occur, regardless of the load condition. This suggests that the torque-speed curve could be a sensitive indicator of the running condition of a synchronous generator wind turbine. Inspired by this idea, a new condition monitoring technique will be developed in this paper. According to Eq.(1), have

$$\omega_s = \frac{\omega_r}{r_g} \tag{2}$$

Henceforward, the rotational speed used in this paper will be that of the generator ω_s.

According to [8], the following relations exists for the relationship between the torque and speed of a synchronous generator wind turbine:

$$\begin{cases} T \propto \dfrac{\omega_s}{X_a} \\ T_{pm} \approx T \end{cases} \tag{3}$$

where X_a stands for the synchronous reactance of the generator, and T_{pm} represents the mechanical torque created by wind force.

With the aid of Eq.(3) the proposed technique will use a criterion C as a versatile function for monitoring the running condition of the wind turbine:

$$C = \frac{T}{\omega_s} \tag{4}$$

where T is the torque and ω_s the generator rotational or synchronous speed, both measured on the generator shaft. It should be noted that the rotational speed shown in Fig.3 is the DC motor speed ω_r measured by using a tachometer mounted on the motor. *C* can be used not only to monitor the presence of a drive train mechanical fault, but also can be employed to detect the occurrence of a generator electrical fault because a drive train mechanical fault will have response in T_{pm} and a generator electrical fault will have response in X_a. One more advantage of criterion *C* is that it is independent of the variable wind demonstrated by the linear relationship between the shaft torque T_{pm} and rotational speed ω_r shown in Fig.3.

4 WAVELET TRANSFORMS

The mechanical and electrical signals from wind turbines comprise complex instantaneous information in both time and frequency domains. The shaft torque and speed signals are also very noisy. Therefore wavelet transforms have been employed to process the data in this paper, the DWT is applied to remove noise and the CWT to extract time-frequency features. In conception, wavelets are a family of functions obtained by the dilation and translation of a mother wavelet $\psi(t)$. The daughter wavelets $\psi_{a,b}(t)$ at scale a and translation b may be expressed as

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{5}$$

The CWT of a signal $x(t)$ is implemented by following the equation

$$CWT_{a,b}(t) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)dt \tag{6}$$

The dyadic discrete wavelet transform, DWT, is a special form of the CWT with dilation $a = 2^j$ and translation $b = 2^j n$, i.e.

$$DWT_{j,n}(t) = CWT_{2^j,2^j n}(t) = \frac{1}{\sqrt{2^j}}\int_{-\infty}^{\infty} x(t)\psi\left(\frac{t}{2^j} - n\right)dt \qquad (j,n \in Z) \tag{7}$$

By using the DWT, the signal being investigated is decomposed into a series of sub-signals with different frequencies, i.e.

$$x(t) = \sum_{n=-\infty}^{\infty} a_{0,n}(t)g_{0,n}(t) + \sum_{j=0}^{\infty}\sum_{n=-\infty}^{\infty} d_{j,n}(t)h_{j,n}(t) \tag{8}$$

where $g(t)$ is a low-pass filter and $h(t)$ is a high-pass filter. Therefore, the first term in Eq.(8) with high frequencies and shows the 'details' of the signal; the second term with low frequencies and shows the 'approximations' of the signal.

The de-noised signal $\hat{x}(t)$ is reconstructed by using the same equation but with the trimmed wavelet coefficients $\hat{a}_{0,n}(t)$ and $\hat{d}_{j,n}(t)$, i.e.

$$\hat{x}(t) = \sum_{n=-\infty}^{\infty} \hat{a}_{0,n}(t) g_{0,n}(t) + \sum_{j=0}^{\infty} \sum_{n=-\infty}^{\infty} \hat{d}_{j,n}(t) h_{j,n}(t) \tag{9}$$

Currently, two thresholding approaches are popularly used to trim the wavelet coefficients. They are

- Hard thresholding:

$$\hat{d}_{j,n}(t) = \begin{cases} d_{j,n}(t) & if \quad |d_{j,n}(t)| > \theta \\ 0 & if \quad |d_{j,n}(t)| \le \theta \end{cases} \tag{10}$$

- Soft thresholding [9]:

$$\hat{d}_{j,n}(t) = \begin{cases} d_{j,n}(t) - \theta & if \quad d_{j,n}(t) > \theta \\ 0 & if \quad |d_{j,n}(t)| \le \theta \\ d_{j,n}(t) + \theta & if \quad d_{j,n}(t) < \theta \end{cases} \tag{11}$$

In the equations, the threshold θ is estimated by following equation (9)

$$\theta = \sigma \sqrt{2 log(N)} \tag{12}$$

where σ is an estimate of the noise level, N is the number of wavelet coefficients in the current level.

The calculation of $\hat{a}_{0,n}(t)$ is similar as that of $\hat{d}_{j,n}(t)$. Both the aforementioned thresholding strategies have advantages and disadvantages of their own. In this paper, the soft thresholding approach is adopted so that the smoothness of the de-noised signal can be guaranteed.

5 CONDITION MONITORING OF THE WIND TURBINE

In order to verify the effectiveness of the proposed technique in wind turbine condition monitoring, two illustrative examples are given in the following. One is detecting a stator winding fault in the generator; another is detecting a rotor imbalance fault in the wind turbine.

5.1 Stator Winding Fault in the Generator

A stator winding fault in the generator was simulated on the test rig by simultaneously shorting 3 coils installed on the stator of the generator. As shown in Fig.4, the 3 coils are equally distributed on the stator by a spherical angle 37^o. They are well connected or shorted with the aid of remote relays connected to them. When the connection state of the coils was alternated periodically, the torque and rotational speed signals were collected from the generator shaft. The time-waveforms of the signals are shown in Fig.5.

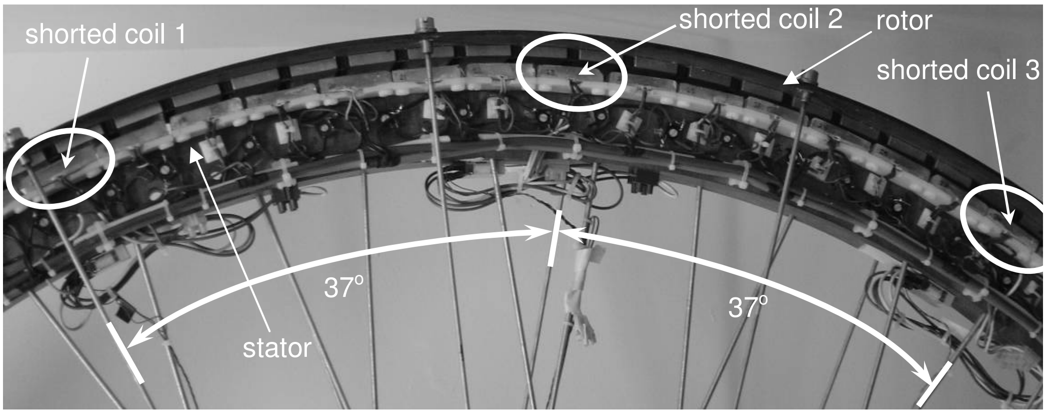

Figure 4: Arrangement on the generator for simulating a stator winding fault by shorting coils

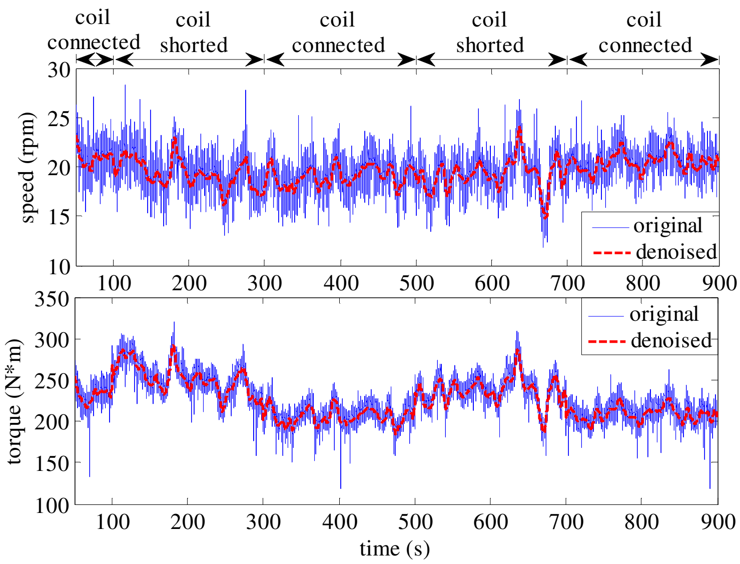

Figure 5: The torque and speed signals when the coils are well connected and shorted

From Fig.5, it can be seen that the shaft torque and rotational speed are indeed very noisy as stated above. So a de-noising process is essential to perform before using them to calculate criterion *C*. By using the wavelet-based de-noising technique depicted in Section 4, the signals are de-noised and plotted in Fig.5. From Fig.5, it is clearly seen that the noise contained in the original torque and speed signals has been successfully removed. Then, the criterion *C* is calculated and the results are shown in Fig.6, in which the results obtained from the original signals are also shown for comparison.

Fig.6 shows that the criterion increases sensibly when the coils are shorted, and returns to normal when the coils are well-connected. Clearly, the stator winding fault in the generator has been successfully detected using the proposed technique. The corresponding decrease of the synchronous reactance X_a of the generator when the coils are shorted accounts for the increase of *C*. In other words, when the coils are shorted, X_a decreases and therefore the torque T created at the same speed ω_r increases. In consequence, the value of *C* increases accordingly.

5.2 Rotor Imbalance Fault

One more proof for demonstrating the effectiveness of the proposed technique in wind turbine condition monitoring can be given by the detection of a rotor imbalance fault. It is known that wind turbine rotors are prone to unbalance due to [4~5]:

- Water in the blade,
- Icing on the blade surface,
- Impact damage to the blade.

Once the rotor is imbalanced a strong vibration at the shaft rotational frequency will be introduced into the system. It travels along the wind turbine drive train, and finally arrives at the generator and a dynamic air-gap eccentricity fault is introduced into the generator. The characteristic frequency of this type of fault will be the rotational frequency of the shaft where the imbalance happens.

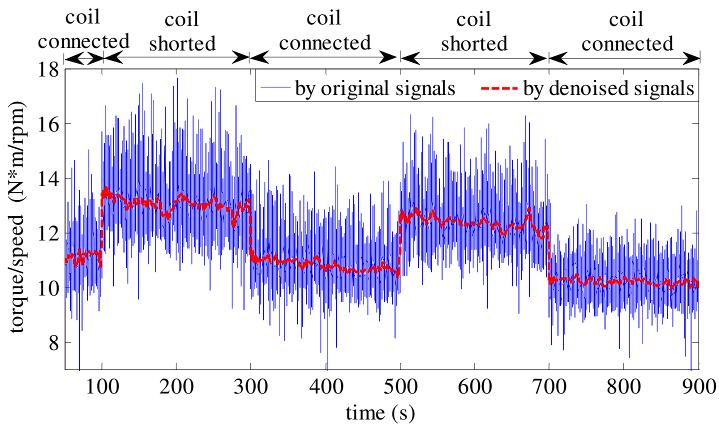

Figure 6: Criterion *C* derived in the case of generator winding fault

A rotor imbalance fault was simulated on the test rig by directly attaching a 1.027kg weight mass to the outer surface of the generator rotor, as shown in Fig.7, which introduced a periodic air-gap fluctuation between the stator and rotor of the generator. The shaft torque and rotational speed signals collected before and after the attachment of the unbalance mass are shown in Fig.8.

The DWT was applied to remove the noise before performing the calculation of criterion *C*. The de-noised signals are also plotted in Fig.8, from which a significant fluctuation of shaft torque due to the unbalance mass is clearly observed. This indicates that the balance condition of the rotor does have a significant influence on the stability of the whole wind turbine. By using the de-noised signals, the criterion *C* is calculated and the calculation results are shown in Fig.9, in which the results derived directly from the original signals are shown for comparison.

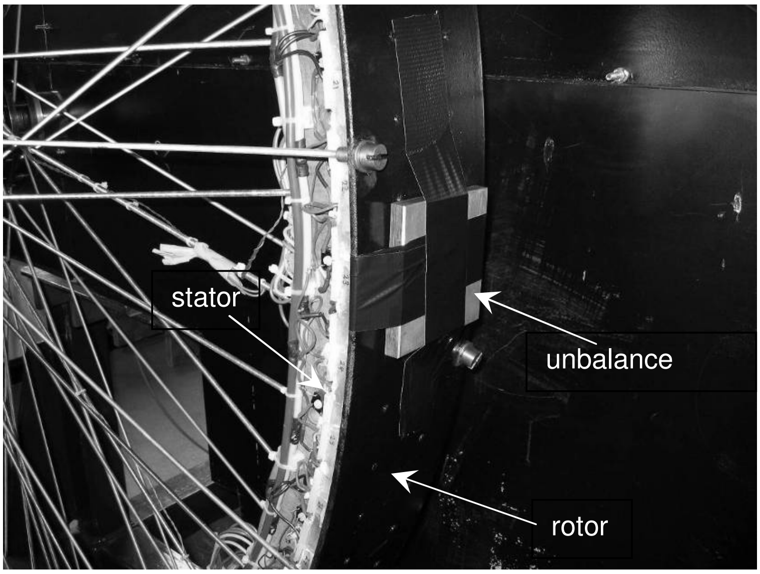

Figure 7: Simulation of a rotor imbalance fault

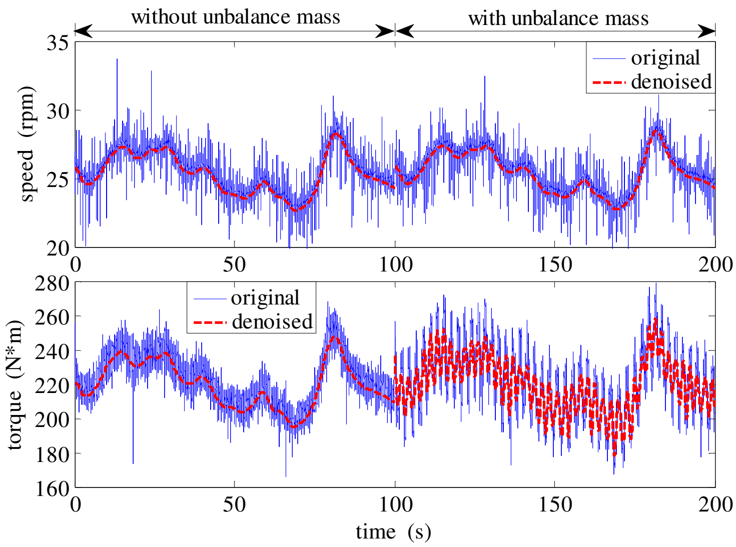

Figure 8: The torque and speed signals in the case of rotor imbalance fault

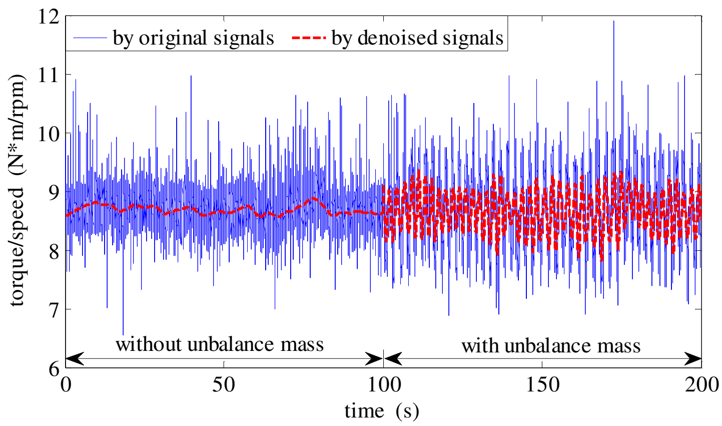

Figure 9: Criterion *C* in the case of rotor imbalance fault

From Fig.9, it is found that criterion *C* shows a large fluctuation when the unbalance mass is attached, becoming stable again as soon as the unbalance mass is removed. Thus, it can be concluded that rotor imbalance can be successfully detected using the proposed technique.

Both Figs.6 and 9 reveal that the application of wavelet-based de-noising strengthens the application of criterion *C* to the condition monitoring of wind turbines.

6 DIAGNOSING MECHANICAL FAULTS BY POWER SIGNAL ANALYSIS

The vibro-acoustic approach is currently popular for diagnosing the mechanical faults presented in the rotor blade, gearbox, bearing, pitch control system and the nacelle of the wind turbine [4]. However, this approach involves the use of a number of transducers and a consequent cost, for example a system recently developed by Bently Nevada [10] includes measurement of:

- Power,
- Shaft torque,
- Wind speed,
- Accelerometers in 8 locations (2 for the nacelle, 1 for the main bearing, 3 for the drive train and 2 for the generator),
- Displacement transducers in 2 locations,
- A keyphasor transducer.

The motion transducers are not able to work independently and must be connected to a dedicated data acquisition/processing device known as a Dynamic Scanning Module (abbreviated as DSM) mounted in control cabinet in the nacelle. This sort of condition monitoring systems is sophisticated and costly and probably cannot be justified except for the most high risk locations. Moreover, the compact nature of the wind turbine nacelle means that installation of the transducers is not easy. Reducing the number of transducers required for condition monitoring is strongly recommended. In the above sections the proposal to condition monitor a wind turbine by using its shaft torque and rotational speed signals has been discussed in detail. Subsequently, the possibility of detecting the wind turbine mechanical faults using power signal analysis will be investigated. If this works, the number of transducers fitted to a wind turbine could be significantly reduced. There is no doubt that a novel condition monitoring and fault diagnosis system consisting only of power, torque and wind velocity transducers, will be much cheaper than a scheme such as proposed in [10] and will therefore be more favourable to wind turbine users.

To prove the feasibility of reducing the number of transducers, a rotor imbalance fault will be diagnosed using the terminal power signal of the generator, this was an approach first advocated by [5]. As depicted in Section 5.2, the unbalanced rotor was simulated by attaching an unbalance mass to the rotor (see Fig.7). Before and after the unbalance mass was attached, the phase current, voltage and power signals were monitored and their time-waveforms are shown in Fig.10.

From Fig.10, no significant difference is visible between the signals collected before and after the unbalance mass was attached. But according to the predictions given in Section 5.2, a characteristic frequency component should occur when the imbalance happens. For the present experiment, this characteristic frequency is at the rotational frequency of the generator rotor. In order to detect this faulty feature CWT is applied to the power signal shown in Fig.10, and the calculation results are shown in Fig.11.

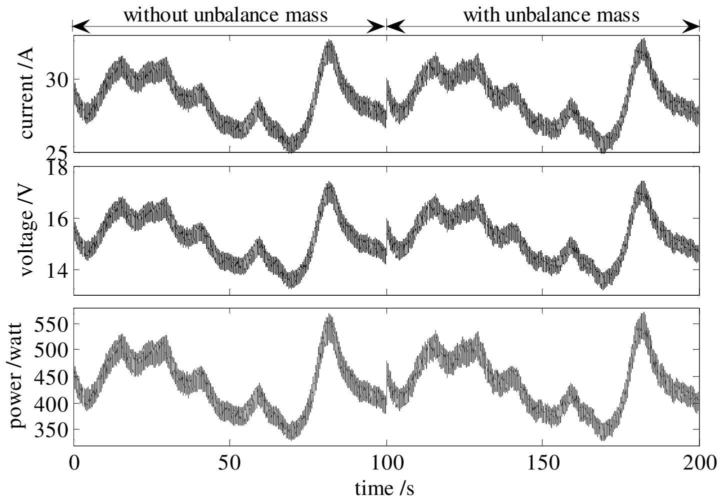

Figure10: Electrical signals in the case of rotor imbalance fault

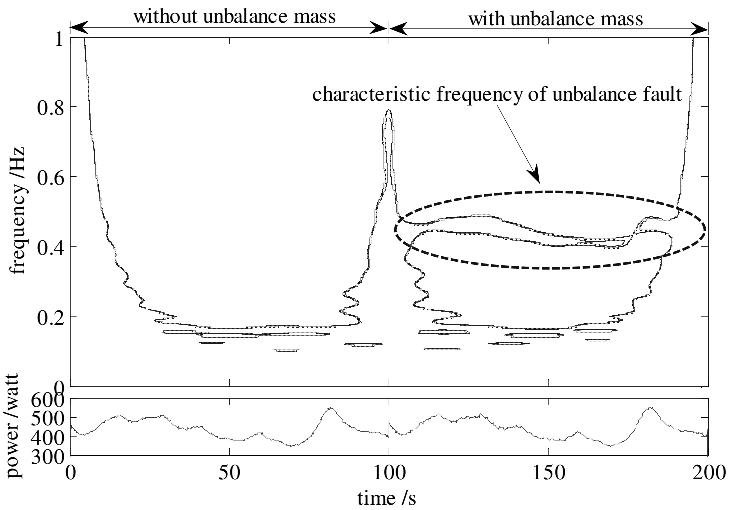

Figure 11: The CWT map of the power signal shown in Figure10

From Fig.11, it is clearly seen that when the imbalance occurs a characteristic frequency appears at about 0.44Hz, corresponding to the rotational speed of 26 rev/min (see Fig.8). The feature extracted by the CWT from the power signal is in accordance with the theoretical prediction thus demonstrating that the detection of mechanical faults by analyzing generator terminal power signal is feasible for a wind turbine. The experiment also proved the value of the CWT for in analyzing non-stationary signals and a faulty feature, created by imbalance, was explicitly identified, though the unbalance mass was light compared to the generator rotor mass.

7 CONCLUSIONS

Condition monitoring and fault diagnosis techniques were investigated in this paper for a wind turbine with a synchronous generator. Firstly, a new condition monitoring technique was proposed based on the phenomena observed in a series of full and half load experiments. Then, the proposed technique was verified by detecting generator winding and rotor imbalance faults. In order to meet the need of developing a simpler and cheaper wind turbine condition monitoring and fault diagnosis system, the possibility of detecting a wind turbine mechanical fault by power signal analysis was investigated with the aid of the CWT. It has been concluded from these preliminary investigations that:

- When the condition monitoring test rig suffered a generator electrical or mechanical fault, the change of running condition was correctly detected using the condition monitoring technique proposed, based upon the criterion $C = \frac{T}{\omega_s}$, rather than by using traditional vibration signals.
- The DWT has a powerful denoising capability for wind turbine signals. The application of the DWT strengthens the viability of the proposed technique in detecting changes of wind turbine running condition.
- The feasibility of detecting a wind turbine mechanical fault through analyzing the generator power signal using the CWT technique has been demonstrated.

It should also be possible, using wind velocity and power transducers, to develop a simple and cheap wind turbine condition monitoring and fault diagnosis system, without resorting to costly vibro-acoustic transducers.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

[1] E.ON Netz. Wind report 2004. *Technical Report*, 2004.

[2] P.J. Tavner, J. Xiang and F. Spinato : Reliability analysis for wind turbines, Wind Energy, Vol.10, 2007, 1-18.

[3] Z. Hameed, Y.S. Hong, Y.M. Cho, S.H. Ahn and C.K. Song : Condition monitoring and fault detection of wind turbines and related algorithms: A review, Renewable & Sustainable Energy Reviews, 2008, In Press.

[4] P. Caselitz and J. Giebhardt : Rotor condition monitoring for improved operational safety of offshore wind energy converters, ASME Transactions, Journal of Solar Energy Engineering, Vol.127, 2005, 253-261.

[5] W. Q. Jeffries, J.A. Chambers and D.G. Infield: Experience with bicoherence of electrical power for condition monitoring of wind turbine blades, IEE Proceedings, Vision, Image and Signal Processing, Vol.45, No.3, 1998, 141-148.

[6] M R. Wilkinson, F Spinato, P J. Tavner : Condition monitoring of generators & other subassemblies in wind turbine drive trains. IEEE Int Conf SDEMPED, Cracow, Septembre 2007.

[7] W.X. Yang, J.B. Hull and M.D. Seymour: A contribution to the applicability of complex wavelet analysis of ultrasonic signals, NDT & E International, Vol.37, 2004, 497-504.

[8] M. S. Sarma: Synchronous machines (Their theory, stability, and excitation systems), Gordon and Breach Science Publisher, New York, 1979.

[9] L.D. Donoho : De-noising by soft-thresholding, IEEE Transaction, Information Theory, Vol.41, 1995, 613-627.

[10] T.J. Clark, R.F. Bauer and J.R. Rasmussen: Wind power comes of age, Orbit, 2004, 20-27.

Development Of A Test Rig For Condition Monitoring Offshore Wind Turbines

C.Crabtree, P.J.Tavner

New & Renewable Energy Group, School of Engineering, Durham University, Durham DH1 3LE, UK

ABSTRACT

This paper describes a test rig for the development of condition monitoring techniques for offshore wind turbines (WT). The test rig incorporates key features of a WT drive train including variable, low speed driving shaft, step-up gearbox, generator and grid electrical connection. The test rig is driven at variable speed, emulating conditions from wind driving, from a National Instruments LabVIEW control and data acquisition (DAQ) environment capable of recording data from various transducers along the drive train. Fault-like perturbations are applied to the test rig and data is recorded and analysed with the aim of identifying faults globally through a reduced set of transducers.

KEYWORDS

Wind Turbine, Condition Monitoring, Test Rig

1 INTRODUCTION

Offshore WTs are increasingly being seen as a promising source of renewable energy. Improved wind conditions offshore offer increased wind speed and capacity factor but in a harsher operating environment. If offshore wind is to be taken up by industry it must be capable of providing a reliable and consistent supply of energy. Through effective condition monitoring and diagnostics it should be possible to see the onset of faults on remote offshore turbines and plan for preventative maintenance before failure occurs.

A turbine drive train, whilst being a low speed machine, is subjected to a highly dynamic speed input. Although condition monitoring techniques are implemented on offshore WTs these have been developed on higher speed machines in an industrial environment. The Durham test rig aims to develop techniques for these low speed machines and gain a greater understanding of the characteristics frequencies associated with different faults within the drive train. The research aims to understand and verify the behaviour of the Durham test rig through characterisation of the torsional behaviour and natural response.

c.j.crabtree@durham.ac.uk

The paper will firstly describe the test rig and its components before discussing control, instrumentation and data acquisition (DAQ).

A survey of failure rates by Tavner et al. [1], shown in Figure 1, has highlighted why the drive train is such an important area for monitoring. Whilst the grid or electrical system and 'other faults' have the highest number of individual failures the combined number of faults from the drive drive components is far greater, particularly when the number of hours of downtime per failure is considered.

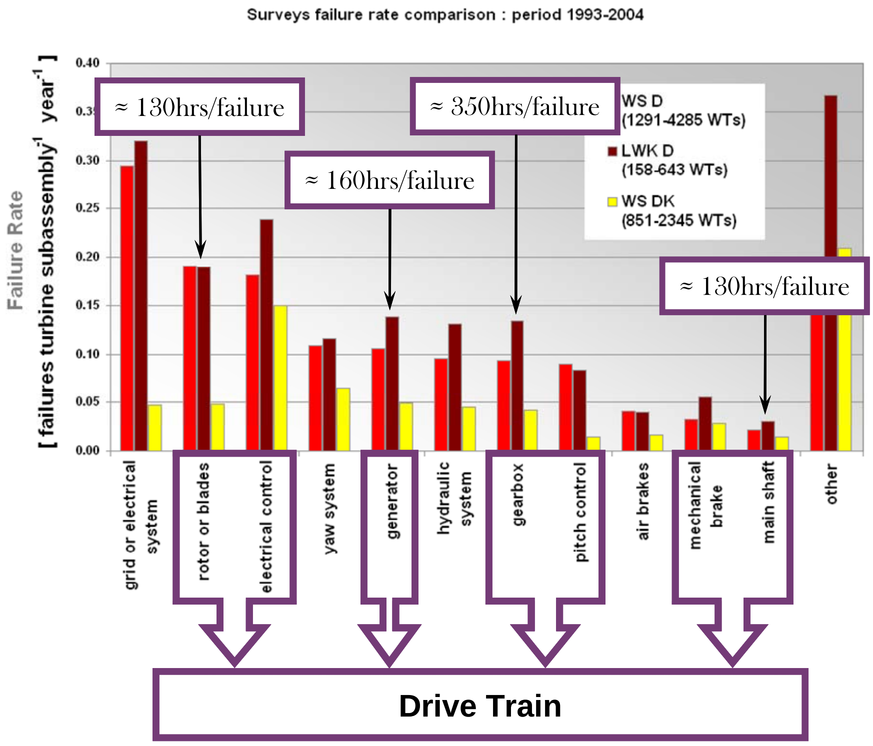


Figure 1 Wind Turbine Failures - Tavner et al. 2008

2 THE DURHAM TEST RIG

2.1 Drive Train Layout

The drive train is driven by 54kW DC motor via a variable speed drive. A LabVIEW control environment reads shaft speed data from a driving file and outputs a voltage signal to the variable speed drive which is representative of the demand speed.

The low speed shaft feeds through a two stage gearbox which increases the speed to that required to drive the wound rotor induction machine (WRIM) above its synchronous speed. The WRIM has resistive load banks connected across the rotor windings which can be varied to emulate a rotor unbalance fault. Figure 2 shows the drive train layout.

Phase current and voltage transducers feed information both waveform and RMS data back to the LabVIEW environment where it is recorded alongside high speed shaft torque, x-y proximeter values and speed signals from both the DC drive end and high speed shafts.

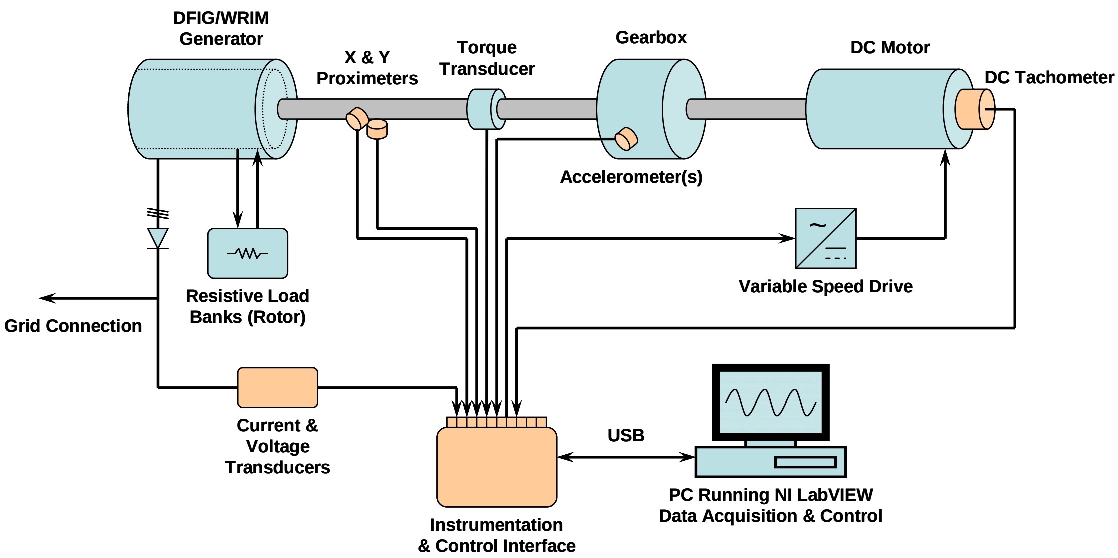


Figure 2 - Drive Train Test Rig Layout

The drive train can be subjected to fault-like perturbations both electrically and mechanically. The rotor winding resistance can be unbalanced by changing the resistance of the three phase load banks connected into the rotor circuit. Mechanical imbalance can be applied by attaching mass to the generator end of the high speed shaft.

2.2 Driving Conditions

Although the test rig can be driven at constant speed it is most important that it can be driven in a stochastic fashion comparable to conditions seen by a WT drive train. As part if the Supergen Wind Consortium, the University of Strathclyde has developed a detailed mode of a 2MW exemplar turbine which has provided shaft speed data to drive the Durham test rig. The conditions chosen are at two different mean wind speeds, 7.5m/s and 15m/s, and two levels of turbulence of 6% and 20% which are representative of normal and turbulent conditions offshore. Figure 3 shows two of the wind driving conditions and their associated rotor speed as derived from the Strathclyde model. The data is then scaled to speeds suitable for the test rig in such a way that the turbulence levels remain correct according to the relationship in (1), below.

$$Turbulence\ (\%) = \frac{\sigma}{\bar{v}} \times 100 \qquad (1)$$

where :

σ = Standard Deviation of Wind Speed (m/s)

$\bar{v}$ = Mean Wind Speed (m/s)

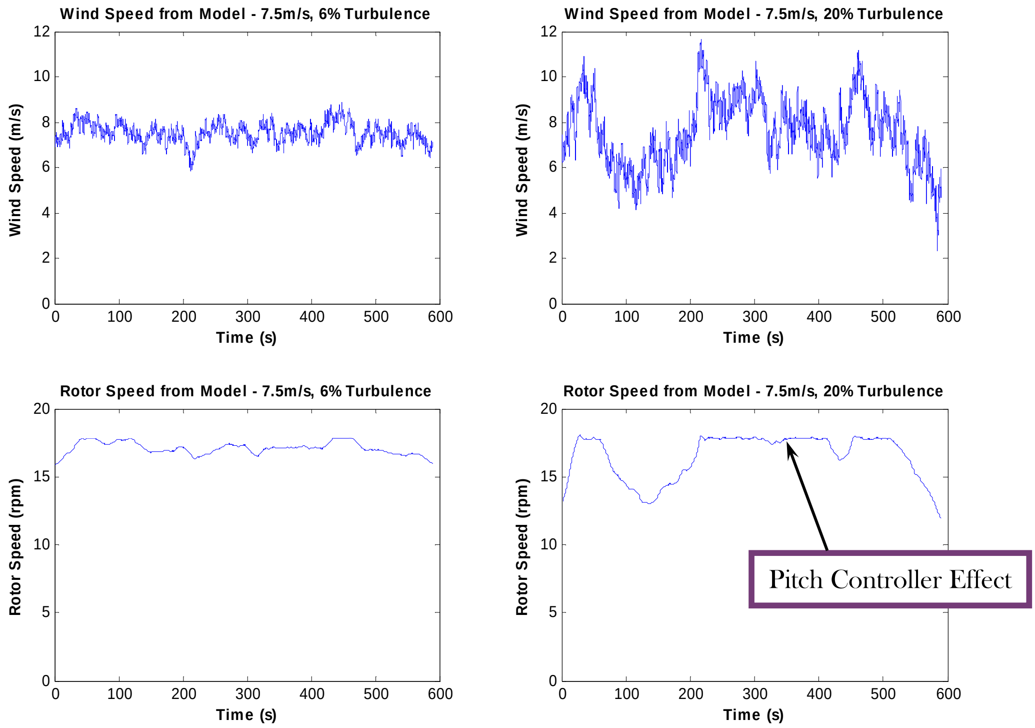


Figure 3 - Low Speed Wind Driving Conditions at Two Turbulence Levels

3 RESULTS FROM THE DURHAM TEST RIG

3.1 Power Signal in the Time Domain

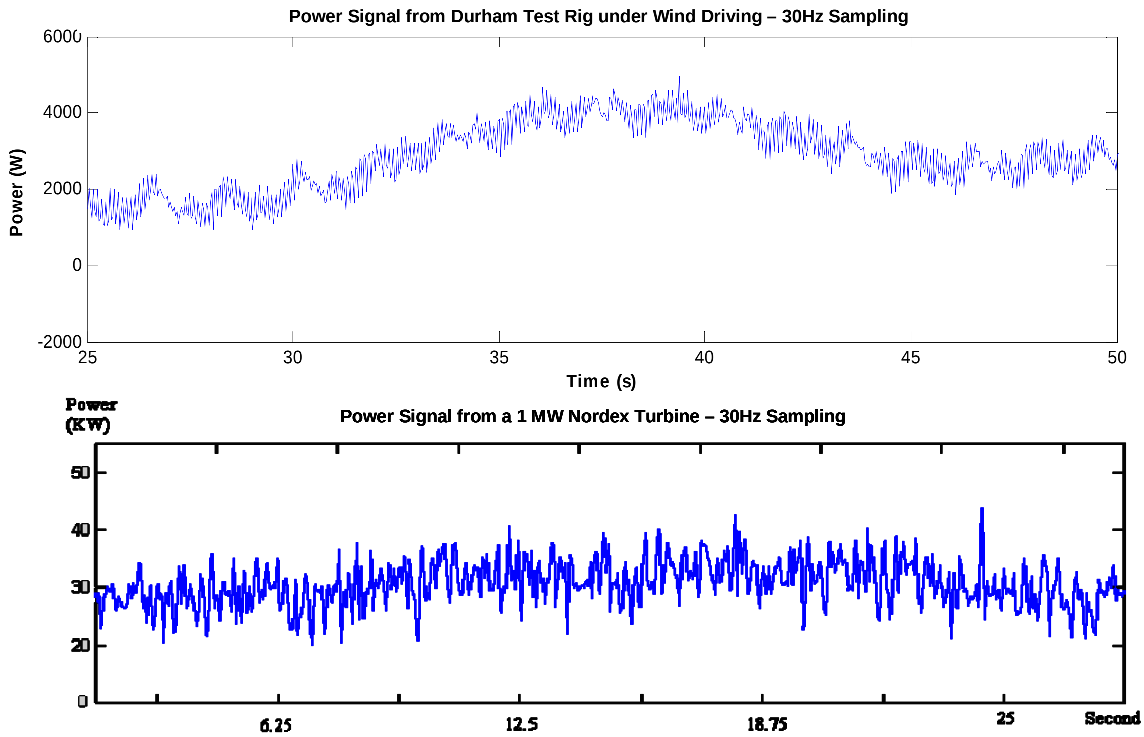


Figure 4 - Comparison of Test Rig Power Signal and a Real Turbine Power Signal

By driving the test rig at variable speed a time varying power signal was obtained. Figure 4, above, shows a comparison between the power signal from the Durham test rig and that of a 1MW Nordex turbine. It can be seen that many of the characteristics are the same but, most importantly, that the power signal is constantly varying with time. This is appropriate for the development of monitoring techniques which will have to cope with varying speeds, torques and powers in a real WT environment.

3.2 Electrically Faulted Operation – Power Signal in the Frequency Domain

Figure 5 shows the frequency content of the test rig power signal over a time period where electrical fault-like perturbations have been applied. The perturbation is applied over two periods of the test run. From the frequency spectrum it is clear that the fault can be observed in the power signal. This is a powerful result as it demonstrates that faults could be detected in a globally available signal.

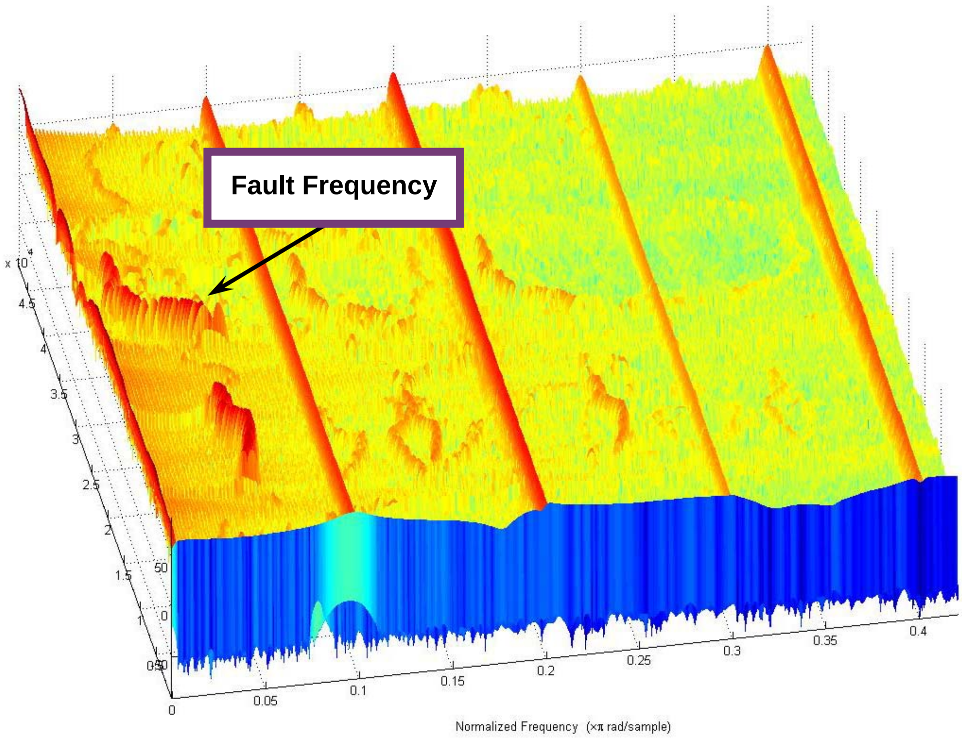


Figure 5 - Frequency Spectrum of Faulted Power Signal

4 CONCLUSIONS

The Durham Test Rig is capable of emulating the key features of a wind turbine drive train, most importantly the variable speed nature of the machines and the non-stationary signals available for monitoring. It has been demonstrated that fault like perturbations can be observed in the globally available power signal. The control environment is capable of driving the test rig at variable speed and recording the various signals for offline analysis.

Future work will increase the number of available fault-like perturbations and continue to make the test rig yet more comparable with a real wind turbine drive train.

BIBLIOGRAPHY

[1] Tavner, Spinato, van Bussel, Koutoulakos, Reliability of Different Wind Turbine Concepts with Relevance to Offshore Application, EWEC, April 2008

No limits for a full electricity supply by renewables

Reinhard Mackensen

ISET e.V. Germany

ABSTRACT

This work inspects the situation of renewables in Germany and points out strategies to integrate a maximum of distributed electrical generation (DG) produced by renewable energy sources (RES). For this the characteristics and future potentials of the different sources are shown. The needs of the electrical system like congestion management, voltage control and further requirements for integrating RES are defined and possible solutions are developed. Pros and cons of energy storage or long distance transmission for integration of DG/RES are discussed. Further on it will be defined which power plant type is needed at what time.

KEYWORDS

Integration, Control strategies, virtual power plants, combi plants

1 INTRODUCTION

One of the main tasks of all economic systems is to secure energy supply. Germany has to face several tasks. A worldwide growing energy demand comes along with decreasing energy resources. Based on the fact that over 60% of the primary energy [STBA07] for Germany has to be imported in the form of fossil fuels the price for electrical energy for industry and private households will grow [SIMM05]. Furthermore the European Union made ambitious decisions regarding CO2 reduction in the next years. A third important fact is the planned phase out of nuclear power in Germany until 2021 and the necessary substitution of 20-25% of the national production of electricity [STBA07].
To use energy from renewables with highest efficiency, the concept of a virtual power plant was developed with the aim to supply Germany with 100% renewable energy sources.

2 THE CONCEPT OF THE RENEWABLE COMBI PLANT

The components of the virtual power plant are energy producers with different characteristics, which are combined with the aim to produce a certain amount of energy [ARW06].

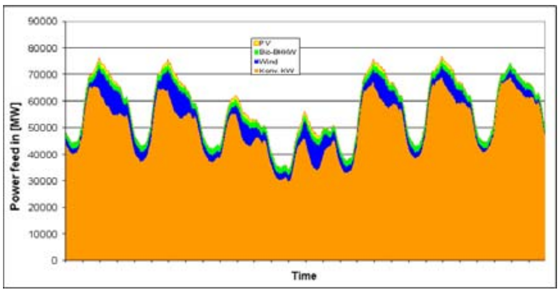


Fig. 1 Weekly power demand (Thursday to Thursday) in MW

In the case of the Combi Plant the objective is to cover the load, which is produced by conventional power plants. This load is calculated from the vertical grid load by adding all decentralized generation. In the case of the Combi Plant existing renewable power production has to be added. Decentral combined heat power system (CHP) are not considered, because the production can not be influenced and will be assumed as constant. So is the electrical power production by waste incineration and

rmackensen@iset.uni-kassel.de

small hydro plants. The result is the German demand for electrical energy of 411,3 TWh for one year. This power demand is shown fig 1 for one week (Thursday to Thursday) as an example.

3 SCENARIO FOR A FULL POWER SUPPLY OF GERMANY BY RENEWABLE ENERGY SOURCES

The first step to create the scenario is to estimate the potentials of the different energy sources wind, photovoltaics and biomass. In the context of the project the scenario you can see in table 1 has been created.

Tab. 1 Future potentials of renewable energy sources in Germany

Type	Potential [TWh/a]	Remarks
Wind onshore	168	Full load hours: 2.800 Average capacity: 6 MW Number of plants: 10.000
Wind offshore	120	Full load hours : 4.000 Average capacity : 6 MW Number of plants : 5.000
Photovoltaics	60	Full load hours : 850 Average capacity : 70 GW Using 20 % of rooftops
Biogas	110	Gasproduction: 40.000 m^3/ha Efficency: 2,8 kWh_{el}/m^3 Using 17 % of agricultural area
∑	**448**	

4 COMPONENTS OF THE PLANT

Aim of this project is to create a system that makes it electrical possible to supply Germany with energy from renewable sources.

For this, realistic scenarios – from the today's point of view - for the integration of power producers are assumed. The system uses wind- and photovoltaic plants. These fluctuating sources are combined with controllable biogas fired CHP and storage devices. The chosen components represent future scenario in a relation of 1/10000.
The plants are – except for the pumped hydro storage device – real power plants which can be controlled and which energy production is fed into the public grid.

Fig. 2 Components of the Combi Plant

5 CONCLUSIONS

The results show, that the consumption can be covered by the power production without any shortages. Wind, photovoltaics and bio produce more energy than needed by the system. But even in years with an over average power feed in by wind imports of energy are necessary.
The challenge on integrating renewable power generators is to deal with the large portion of fluctuating power feed in. This is why it is necessary to install much more capacities in total than peak load demand. It is obvious, that the system Renewable Combi Plant needs

storage capacities to meet the demand every time. With the higher penetration of fluctuating energy producers the need for an intelligent integration into the supply system rises.

BIBLIOGRAPHY

ARW06 Virtuelle Kraftwerke: Theorie oder Realität?, in: BWK Bd. 58 (2006) Nr. 6, S. 52-57.

DENA05 Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020, 2005, Deutsche Energie-Agentur GmbH, Berlin

EEG00 Gesetz für den Vorrang Erneuerbarer Energien, März 2000

GOLD07 Beitrag über das Kraftwerk Goldisthal, 2007 http://wikipedia.org, abgerufen: 15.05.2007.

IPCC07 4. Sachstandsbericht über Klimaänderungen, 17.11.2007 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bundesministerium für Bildung und Forschung, Weltklimarat der Vereinten Nationen

ROHR03 Rechenmodelle und Informationssysteme zur Integration großer Windleistungen in die elektrische Energieversorgung, Dissertationsschrift 2003, Dr. In. K. Rohrig

RWE07 Netzkennzahlen, 2007 http://www.rwetransportnetzstrom.com/generator.aspx/netznutzung/netzdaten/netzkennzahlen/language=de/id=75454/netzkennzahlen-page.html, accessed: 08.06.2007.

SIMM05 Mathew Simmons, Interview im Züricher Tagesanzeiger, 23.07.2005, http://www. sft.de/sft/bilder/TagesAnzeiger.pdf, abgerufen: 12.06.2007.

STBA07 Bruttostromerzeugung in Deutschland von 1990 bis 2006 nach Energieträgern, 22.08.2007, Statistisches Bundesamt

UCTE08 Website "Union for the Co-ordination of Transmission of Electricity", www.ucte.org, accessed 17.02.2008

HLI reliability analysis of future scenarios for the power system in west Denmark

Barberis Negra N.[1)], Holmstrøm O. [1)], Bak-Jensen B. [2)], Sørensen P. [3)]

[1)] DONG Energy A/S, Denmark, [2)] Aalborg University, Denmark, [3)] Risø-DTU, Denmark

ABSTRACT

This work focuses on the reliability of power systems with a large amount of wind generation. Models of different components of the power system in west Denmark are defined from an HLI point of view and a sequential Monte Carlo simulation is applied. The analysis considers current and future scenarios of the power system, where the wind generation, both onshore and offshore, is increased as well as the system load. Results are presented in form of reliability indices and probability distribution functions. With these studies it is also possible to provide preliminary evaluations for a more detailed HLII investigation.

KEYWORDS

Monte Carlo methods, power generation reliability, wind power generation

1 INTRODUCTION

The planning and secure operation of power systems with large scale dispersed generation is a challenge for system operators: regarding this issue, power system reliability has to be assessed in order to investigate how the power system reacts to large amount of wind generation. In this paper, different models are developed to represent the different components that are part of the power system in west Denmark (WDKPS) and its reliability is evaluated considering current and future scenarios, where the wind capacity and the load are increased. The simulation is performed using a sequential Monte Carlo simulation and a set of reliability indices is calculated: probability distribution functions of the different indices can be easily obtained as well.

2 REPRESENTATION OF THE POWER SYSTEM

In order to perform a sequential Monte Carlo simulation for reliability assessments, it is necessary to represent each type of generation in the system and the load as an hourly time series. The status of the system is then known in each hour of a sample and it is possible to calculate when reliability requirements are not fulfilled and the load cannot be properly supplied. The components modelled here are conventional power plants (CPP), distributed

nibne@dongenergy.dk

CHP generation (CHP), onshore distributed wind generation (WDG), offshore wind farms (OWF) and system load. Models used in this work to represent these elements are available in [1]. The performed analysis is the so-called HLI assessment and transmission facilities are neglected as well as interconnectors with neighbouring countries.

3 SIMULATION RESULTS

The Monte Carlo simulation is applied to current and future scenarios of the WDKPS. Data for the different scenarios are presented in Table 1. Future offshore wind farms are defined according to the current state of the art of offshore wind farms.

Table 1: Installed capacities in each scenario

[MW]	Year	Load peak	Inst. CPP	Inst. CHP	Inst. WDG	Inst. OWF
Scenario 1	2007	3737	3579	1550	2200	160
Scenario 2	2010	3901	3579	1550	2400	369.3
Scenario 3	2025	4597	3579	1550	2400	3434.9
Scenario 4	2025	4597	3579	1550	3200	2225.3
Scenario 5	2025	3945	2317	1550	3200	2225.3

Reliability indices are presented in Table 2 for the entire WDKPS, together with the number of samples and the accuracy reached by index LOEE with the discussed simulation.

Table 2: Reliability results for the five considered scenarios.

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
LOLE	h/yr	0.181	1.126	13.317	16.600	670.315
LOLF	occ/yr	0.472	0.415	4.418	5.416	100.466
LOEE	MWh/yr	58.050	163.065	2369.097	2936.166	203950.039
DOI	h/occ	2.600	2.715	3.014	3.065	6.672
Coeff. of variation	%	5.810	4.167	1.950	1.950	1.950
No. samples	-	10000	10000	4514	3611	251

4 CONCLUSIONS

Presented reliability indices show that the increase of offshore wind generation does not necessarily mean an improvement of system reliability, mainly due to the correlation of power output of different wind parks, i.e. a lack of generation in case of low wind, and due to the capacity factor of wind installations, which cannot be always used to balance the increase of demand or to replace dismantled conventional power plants. Accurate studies are therefore necessary to investigate future developments of the WDKPS to avoid problems for the system balance.

BIBLIOGRAPHY

[1] N. Barberis Negra, O. Holmstrøm, B. Bak-Jensen, and P. Sørensen, "Models for HLI analysis of power system with offshore wind farms and distributed generation", in *Proc. Seventh International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind farms*, Madrid, Spain, May 2008.

Aggregated Wind Power Prediction Method Based on Comparison of Weather Forecasting Vectors

Miguel G. Lobo, Ismael Sánchez

Universidad Carlos III de Madrid. Av. de la Universidad 30, 28911 Leganés (Madrid), Spain

ABSTRACT

When the number of wind farms in an electrical system increases, the wind power prediction methods may require a long time if predictions are calculated for each of the wind farms. When the power provided for each wind farm is irrelevant to the System Operator and what really matters is the total wind power, the use of aggregated wind power prediction methods is faster than predicting each of the wind farms and adding. Aggregated predictions could even be more precise than the sum of individual predictions. This study proposes to make aggregate wind power predictions based on historical weather predictions for a set of points and the total wind power production, using techniques based on statistic distances.

KEYWORDS

Wind power prediction, Aggregated prediction methods, Regional wind power prediction

1 INTRODUCTION

The total wind power installed in Spain in december 2007 reached about 13000 MW [1]. As the number of wind farms increases, the forecasting methods based on making predictions for each wind farm become slower. That makes necesary to find faster methods which make predictions for a complete electrical region, instead of each wind farm.

2 PROPOSED METHODOLOGY

The method proposes to make aggregated wind power predictions for the total region by comparing the new wind speed forecast for a set of points, given by an external meteorological agency, with the historical wind speed forecasts stored.

This method needs a block of historical wind speed forecasts for a set of points, and the historical mesasures for the total wind power generated in a region.

mglobo@ing.uc3m.es

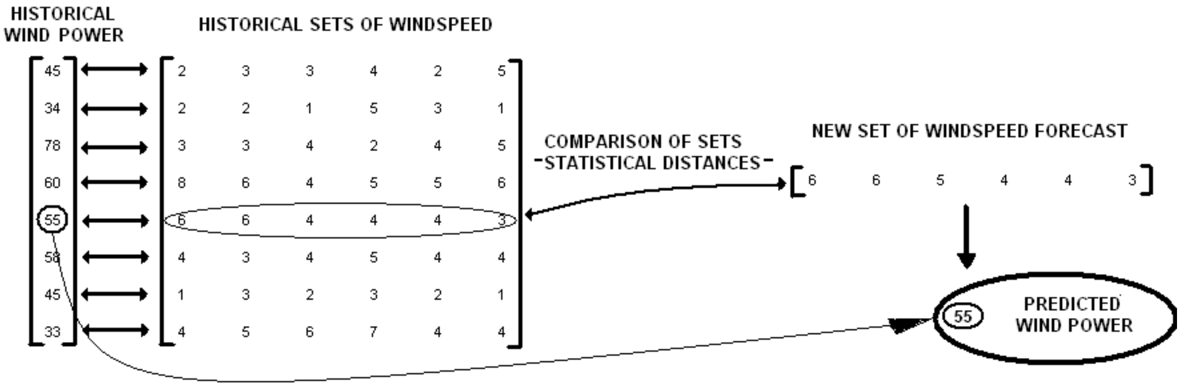


Figure 1: Comparison of windspeed forecast with historical data

The way to compare the wind speed sets is based on statistical distances, following different methodologies explained below. [2] [3][4]

2.1 Absolute distance

The distance between two sets of points as Absolute Distance is defined as

$$d_{t,T+h} = \sum_{k=1}^{k} \left| v_{k,t} - v_{k,T+h} \right|$$

k = number of elements of the wind speed prediction set

h = prediction horizon

T = current time

$v_{k,t}$ = historical wind-speed prediction for the elements of the set for hour "t"

$v_{k,T+h}$ = new wind-speed prediction for the set elements, for "T+h" horizon

$d_{t,T+h}$ = distance betwen stored wind-speed set "t" and predicted wind-speed set "T+h"

2.2 Euclidean distance

The distance between two sets of points as Euclidean Distance is given by

$$d_{t,T+h} = \sum_{k=1}^{k} \left(v_{k,t} - v_{k,T+h} \right)^2$$

The objective will be to minimize the sum of the square of the wind speed diferences.

2.3 Mahalanobis distance

Mahalanobis distance takes into account the correlations of the data set, and is defined as

$$d_{t,T+h} = \sqrt{\left(v_t - v_{T+h}\right)^t \cdot \operatorname{cov}^{-1}\left(v_t - v_{T+h}\right)}$$

cov = covariance matrix

3 EVALUATION AND RESULTS

3.1 Case Study

To make an evaluation, a set of 16 windfarms distributed throughout the spanish power system have been selected. The total nominal power of the selected windfarms was 1450 MW, about 10% of the total installed wind power in Spain.

3.2 Evaluation Method: Mean Absolute Error (MAE)

The mean absolute error is an average of the absolute errors, used to measure how close forecasts or predictions are to the real wind power. The MAE is given by

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|P_{Real,i} - P_{Pred,i}\right| \quad [2][3]$$

3.3 Results

The results obtained for aggregated methods, using diferent statistical distances proposed, are compared with the results obtained from a traditional wind power prediction tool, normally used to make wind power predictions in Spain, which calculates the total wind power prediction by making individual wind power predictions for each wind farm and adding [5] [6] [7].

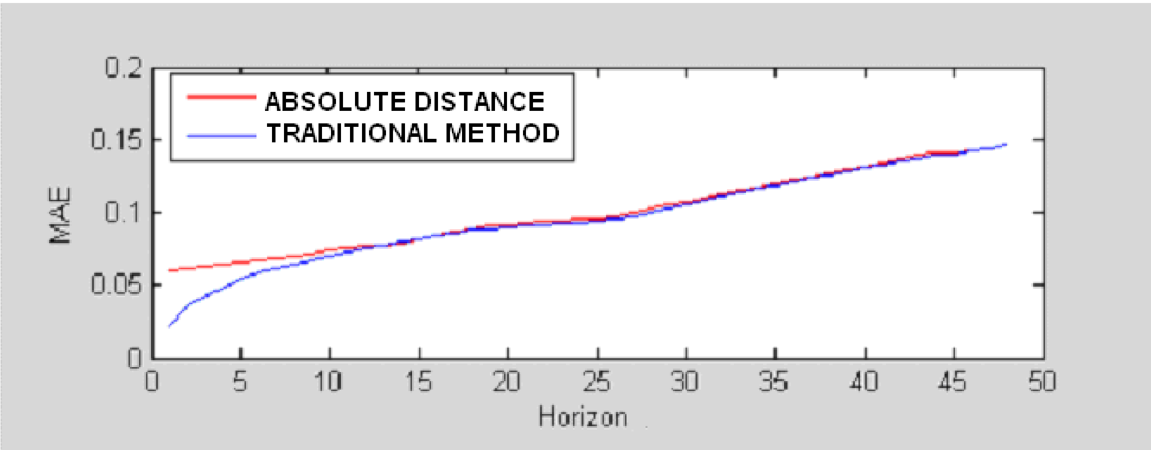


Figure 2: Aggregated method using Absolute Distance vs Traditional method

The results show that the accuracy of wind power predictions calculated by traditional method is better than aggregated methods only for nearby horizons.

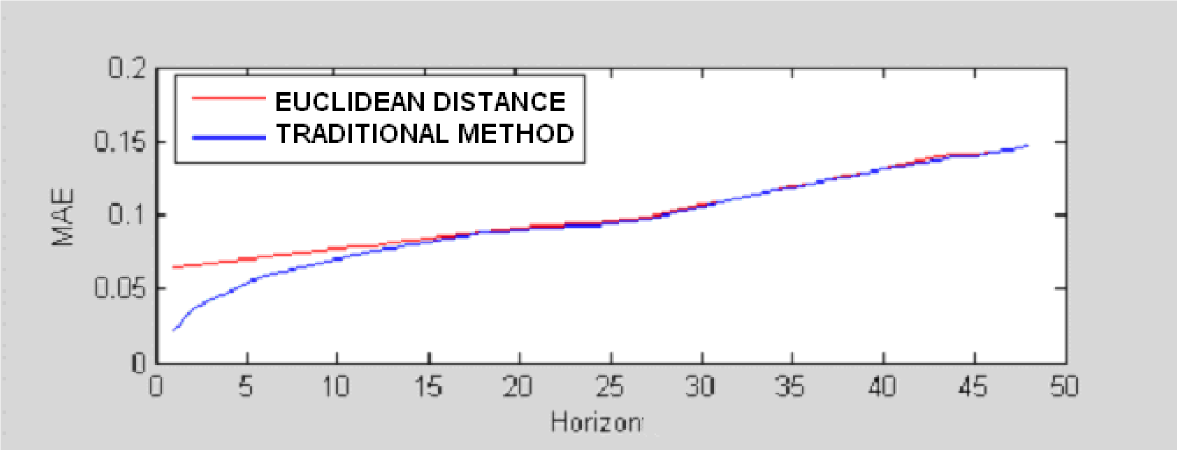


Figure 3: Aggregated method using Euclidean Distance vs Traditional method

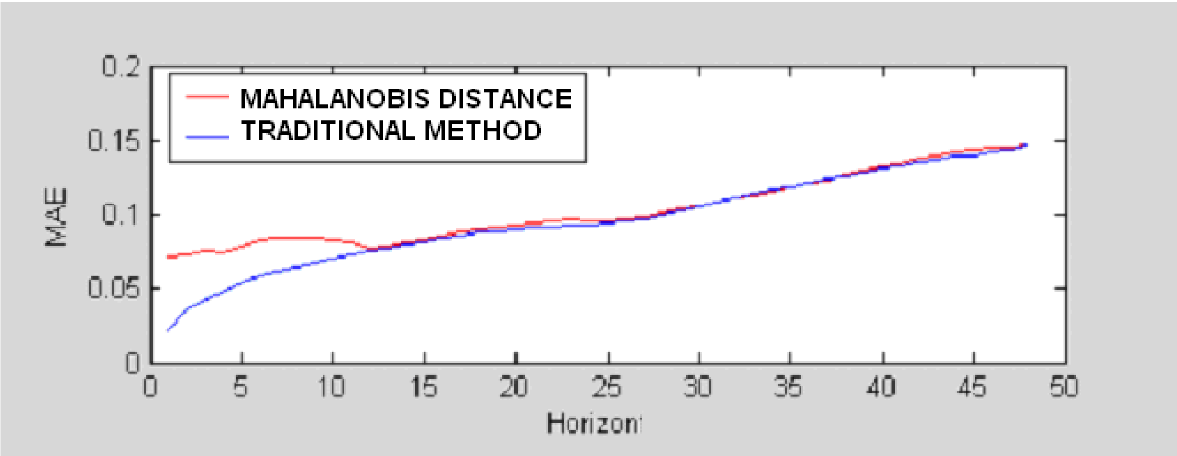


Figure 4: Aggregated method using Mahalanobis Distance vs Traditional method

4 CONCLUSIONS AND FUTURE RESEARCH

This paper gives the basic features of an algorithm for predicting aggregated wind power. While traditional methods that make wind power predictions for each wind farm take a long time to calculate and add, if the specific wind power prediction for each wind farm is not neccesary for the System Operator, aggregated method is a faster and accurate way to make wind power predictions.

Due to the different methods for calculating the statistic distances, it is necesary to research about other methods, and to optimize the way the power is selected: The same power as the set at minimum distance?, average of power for nearest sets of points?, etc

BIBLIOGRAPHY

[1] www.ree.es

[2] www.wikipedia.org

[3] Peña, D. Fundamentos de Estadística. Alianza Editorial.2001

[4] WILLIAN MENDENHALL. Probabilidad y estadística para ingeniería y ciencias. Prentice may Hispanoamérica. 1997.

[5] Usaola. J Et al. Sipreolico, a wind power prediction tool for the spanish peninsular power system operation. Global Wind Power Conference. 2002

[6] I. Sánchez Et al. Sipreólico, a wind power prediction system based on flexible combination of dynamic models. Application to the Spanish power system. World Wind Energy Conference & Exhibition. 2002

[7] G. González Et al. Sipreólico, Wind poser prediction tool for the spanish peninsular power system. CIGRE 40th General Session & Exhibition. 2004

A Deterministic based Genetic Algorithm applied to a Modern Wind Turbine Controller Using Smart Blade Design.

Peter Bjørn Andersen

Ph.D. student at Risø-DTU Denmark

ABSTRACT

The models used in the wind turbine industry today are highly non-linear and do not readily yield to conventional methods used in control theory. The field of metaheruristics offers an alternative way of optimizing a controller, in the form of a Generic Algorithm (GA). The wind turbine controller will focus on reducing loads which can be deterministicly estimated using a Deformable Trailing Edge Geometry (DTEG) mounted on the wind turbine blade.

KEYWORDS

Wind turbine control, deformable trailing edge geometry, metaheuristic genetic optimization.

1 INTRODUCTION

The wind turbine controller in question is optimized using the Genetic Algorithm (GA) principle. Genetic Algorithms are a simulation of nature's genetic process, with emphasis on breeding and the survival of the fittest. Evolution is the natural adaptation of species to the changes around them and the survival of those individuals that do it better. Each solution is an individual of the solution's species. The GA is part of the meta-heuristic family, which again is a heuristic method for solving a very general class of computational problems by combining user-given black-box procedures. Meta-heuristics are generally applied to problems for which there is no satisfactory problem-specific algorithm or heuristic; or when it is not practical to implement such a method.

2 THE GA MODEL

To outline the optimization strategy for the controller the GA process is broking into the following steps: *1. Initialize pool of individuals, 2. Evaluate individuals (fitness), 3. Select individuals, 4. Combine individuals (crossover), 5. Removing an individual (kill), 6. Randomly change individual (mutate), 7. Return individual to the pool, 8. Return to step #2*

An Aero-Servo-Elastic code has been used in collaboration with the GA model presented in this paper. The HAWC2 code developed at Risø forms the basis for this analysis. A series of pools of individuals are created. In total 36 pools are created each with 10 degree azimuth angle (Ω) in total of one full rotor revolution.

peter.bjoern.andersen@risoe.dk

3 RESULTS

Notice in Figure 1 how the uncontrolled wind turbine has a great drop in blade1 root moment at 200 degree azimuth angle primarily due to tower shadow and the shear effect, whereas, the controlled case based on the GA method is close to constant. In fatigue numbers we are looking at a 99.3% fatigue reduction, and equivalent reduction in min/max range. It should of course be noted that all stochastic inputs like turbulent wind is not included in the model.

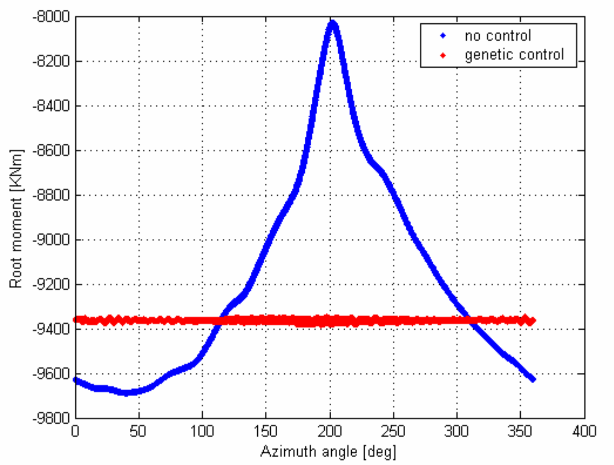


Figure 1; blade root moment for the 5MW reference turbine at 11m/s constant wind.

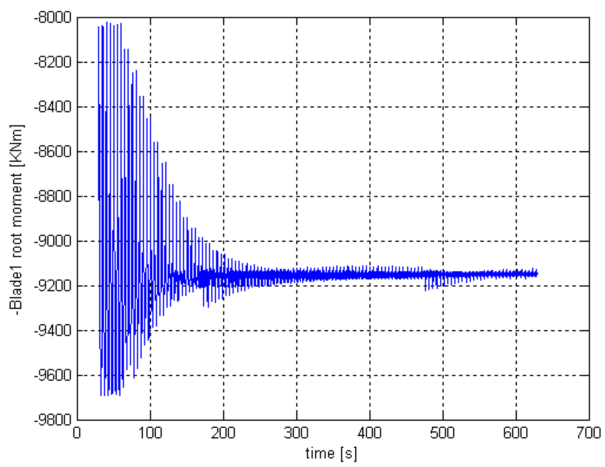


Figure 2; convergence in time using GA, sensor is root moment for blade 1

It is interesting to focus on behavior of the system in terms of convergence. In Figure 2 is shown a typical optimization run where the residual load variation gradually is diminished as the individuals become smarter. What's interesting is the speed with which this seems to occur. It is interesting to see how the GA sometimes chooses an series of individuals with non optimal characteristics and the root moment increases see at time t=180s and t=480s approximately; however, on an overall scale the convergence is undisputable.

4 CONCLUSIONS

The Generic Algorithm (GA) suggested in this paper has shown to perform well regarding optimization of a wind turbine controller. High load reductions haven been seen for blade, yaw and tower bending moment. The work presented in this paper assumes that the GA has (in theory) infinite time to adapt to time-invariant 1P load variations, when subjected to a turbulent inflow the GA model does not perform well.

SESSION 2-B
SIMULATION AND MODELLING
- PART II

(Parallel to the Session 2-A)

Wednesday, 01.10.2008

14:00 – 16:00

Building 22A / Room 020

Supervisor:

Prof. P. Tavner, Durham University

Chairman:

J. Gottschall, ForWind, University of Oldenburg

Rotor-Tower Interaction in HAWTs

Alejandro Gomez[1), Joerg Seume[1)]

[1)] Institute for Turbomachinery and Fluid Dynamics
Leibniz Universität Hannover
Appelstr. 9, 30167. Hannover, Germany

ABSTRACT

A blade passing through the stagnation region in front of the tower of a 3-bladed horizontal axis wind turbine (HAWT) causes impulsive loads on the carrying structure of the turbine with a 3p frequency. Depending on the geometric parameters different flow situations may be expected. These range from simple changes in effective angle of attack up to strong aerodynamic coupling and double dynamic stall hysteresis loops. Using conformal mapping and a Beddoes-Leishman dynamic stall model some of the main features of this interaction are studied. It is found that for rotor-tower separations below approx. 2 tower diameters there exists a strong aerodynamic coupling, and a transient circulation is induced on both bodies.

KEYWORDS
Rotor aerodynamics, Rotor-Tower interaction.

1 INTRODUCTION

The interaction between the tower and the blades of a wind turbine has as consequence dynamic changes in the effective local angle of attack (AOA) α along the span of the blade. The AOA to which the blade elements are subjected to ranges from negative angles up to deep stall angles. For some operating conditions α may vary in such a way that it exceeds the static stalling angle α_{ss} and then quickly falls back to values underneath it. To model these large changes a dynamic stall model is needed. To suit this purpose, a Beddoes-Leishman Dynamic Stall model has been implemented in a State-space formulation [1] which is in the form of a closed set of differential equations which can be solved numerically.

The lift characteristics exhibited by an oscillating airfoil are somewhat different to those which would be expected by a quasi-steady model using the static airfoil aerodynamic data. A first difference is encountered with the onset of stall, which is significantly delayed for the oscillating case in comparison with the stationary case. The delay in the onset of stall is accompanied by an overshoot in the lift coefficient of the profile, but once a stall condition is reached it is even more severe than static stall [2,3]. These effects are especially critical when the oscillation of the profile occurs at angles of incidence near α_{ss}.

gomez@tfd.uni-hannover.de

Dynamic stall is characterized by the shedding of a vortex near the leading edge, which convects along the suction surface of the airfoil inducing an unsteady pressure field which explains some of the features of the airfoil's response.

The dynamic stall model implemented neglects compressibility effects, and assumes trailing edge separating airfoils. The model includes an unsteady inflow velocity in order to model lead-lag blade vibrations. The main features of the model include:

- Attached flow model derived from Theodorsen´s theory [7]
- A description of trailing edge separation based on the Kirchhoff flow past a flat plate
- Dynamic trailing edge separation based on the assumption of a time-lag between pressure and lift, and a lag in the separation point compared to the quasi-steady case derived from the boundary layer equations.

2 UNSTEADY FORCES

2.1 Dipole model of the tower

The influence of the tower on the rotor causes a reduction of the average torque on the main shaft [4] which produces reductions of the power of less than 5% [5]. Although this reduction in output power is important, more detail is needed when considering the aeroelastic and aerodynamic coupling of the structure.

During one revolution the local angle of attack changes due to various factors such as wind shear, yawed flow and tower passage. Whilst yawed flow and wind shear cause rather smooth changes in the AOA, the interaction with the tower causes an impulsive change. For a clear conceptual understanding of this effect one can take a look at the potential solution of the flow upstream of the tower (replacing the tower by dipoles to generate a circular streamline with the same radius as the tower). The reader is invited to follow the following mental experiment: looking downstream at the rotor (the tower is behind the rotor) a blade passes from the left to the right in front of the tower (counter-clockwise rotation). As the flow approaches the tower it is going to be accelerated and deflected at the sides of the tower and decelerated (until stagnation) in front of the tower. When the blade comes from the left it will encounter a region of accelerated flow deflected to the left; afterwards as it is in front of the tower, a region of decelerated flow (mainly in the axial direction) and as it leaves, a region of accelerated flow deflected to the right. The local flow angle can be estimated using the axial and tangential induction factors predicted by the BEM method and it is easily seen that the aerodynamic response of the blade (neglecting inertia of the fluid) is not symmetric with respect to the tower.

Because of the predetermined direction of rotation, the changes in AOA during the tower passage show also asymmetry with respect to the yaw angle (i.e. the tower passage presents different features for positive and negative yaw angles). The asymmetries caused by the tower and the yaw angle can be seen in Figures 1 and 2 for the setup described in Table 1.

Chord	1.446m	*U*	8 m/s
Twist	13.2°	*Lambda*	6
Radial Station	6m	*a (axial induction factor)*	0.324
Turbine radius	20m	*a' (tangential induction factor)*	0.0615

Table 1: Turbine characteristics

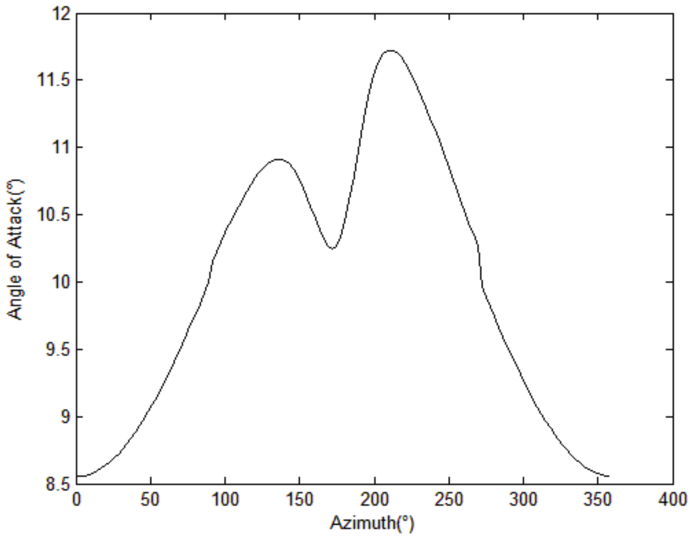


Figure 1: Angle of attack. Yaw=10°

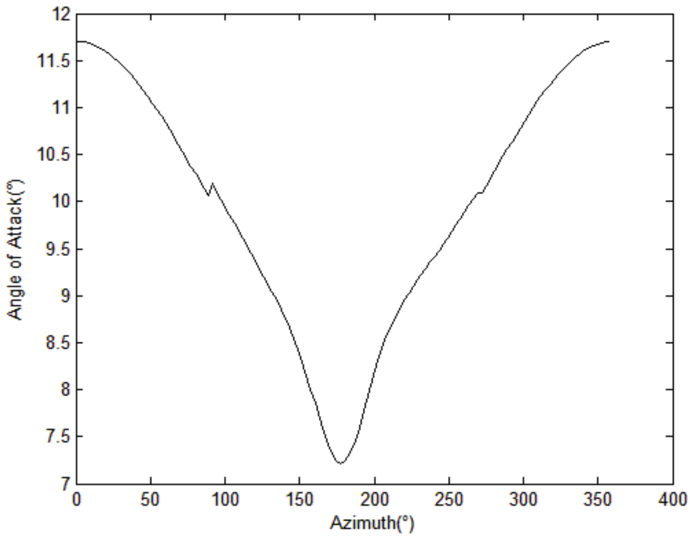


Figure 2: Angle of attack. Yaw=-10°

2.2 Dynamic-Stall Model

A Beddoes-Leishman dynamic stall model is implemented together with a classic BEM formulation to explore the behaviour of a profile section submitted to the changes in AOA described in the past section.

Interesting results arise for configurations similar to the one shown in Figure 1 with two distinct peaks in the angle of attack. These two peaks lead to a very fast change in the circulation around the airfoil, which as predicted by the Beddoes-Leishman model would produce a double overshoot in the lift coefficient during one revolution of the blade. On a c_l vs. α graph, this double overshoot would be represented by a double hysteresis loop, one of which is traversed slowly and the second of which occurs rapidly as the blade passes in front of the tower. According to such behaviour of the AOA, vortex building should be expected on the suction side of the profile. Unsteady simulations have although shown that the building of vortex-structures in the region within the tower and the rotor is greatly restrained because of the acceleration of the flow parallel to the rotor plane. Computational work is being done to study the building and development of vortical structures as a result of the blade passage with initially stalled flow.

3 CFD ANALYSIS

Although the potential flow model for the tower can be used to gain some insight on the problem, it is not very well suited to study the aerodynamic coupling because of the interference of the pressure fields. Stationary computations by means of conformal mapping of doubly connected regions have been previously done to understand the amount of aerodynamical interaction between a lifting body and a cylinder. These computations have shown that for separation distances between 1-2 cylinder diameters the coupling between the two bodies cannot be neglected. This has also been studied in the ROTOW project [6]. Circulations are induced on both bodies and the lift forces on the profile cease to be proportional to the circulation for different angles of attack (although the force on the whole system is of course proportional to the net circulation). As mentioned by Früh [4], the passing of the blade in front of the tower acts as a reattaching mechanism for separated flows. As the blade passes in front of the tower a large deflection of the flow takes place which causes the boundary layer to reattach. The induced circulation on the blade causes at some locations even an inversion of the main flow direction (see Figure 3).

4 CONCLUSIONS

This paper gives an insight to some main flow characteristics occurring during the blade passage in front of the tower of HAWTs. The study of the undisturbed flow around the tower gives some hints which lead to the understanding of the unsteady local flow angle, but is not capable of capturing all the effects which take place. A coupling of a dynamic stall model with the BEM equations may be well suited to study interactions where the aerodynamic coupling is not too large. For small rotor-tower separations transient circulations are induced which change largely the flow pattern and the separation mechanism of the boundary layer.

The preliminary results show that dipole models of the tower are not capable of resolving the flow phenomena caused by the rotor-tower interaction, and further work has to be done to include the aerodynamic (and aeroelastic) coupling of the structure.

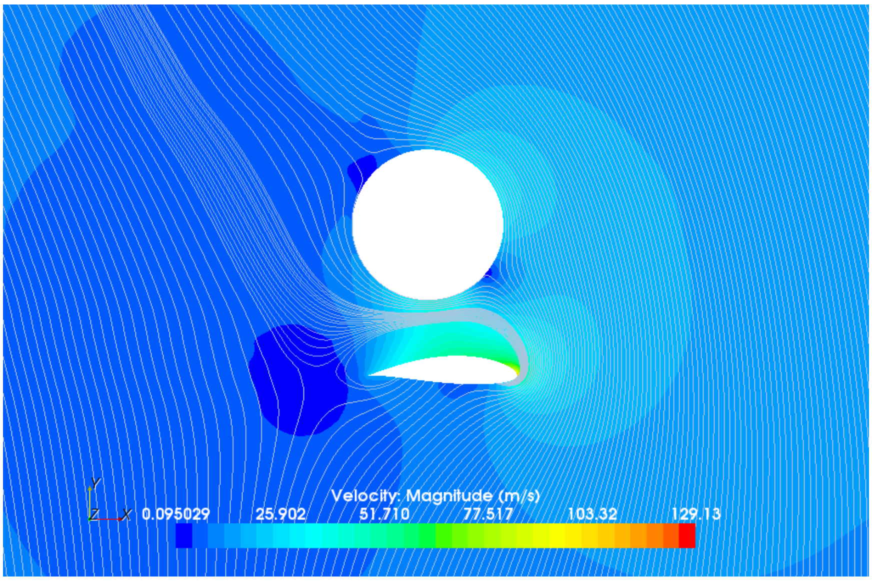


Figure 3: Velocity field in an inviscid simulation of the blade-tower interaction.

BIBLIOGRAPHY

[1] Hansen, M; Gaunaa, M.; Madsen, H.; “A Beddoes-Leishman Type Dynamic Stall Model in State-Space and Indicial Formulations”. Riso National Laboratory, Roskilde, Denmark. June 2004.

[2] McCroskey, W.J., “The Phenomenon of Dynmic Stall”. Nasa Technical Memorandum 81264. March, 1981.

[3] Björck, A. “Dynamic Stall and Three-dimensional Effects”. Final report for the EC DGXII Joule II Project. FFA Aeronautical Research Institute of Sweden. 1995.

[4] Früh, W.G., Seume, J., Gomez, A. “Modelling the aerodynamic response of a blade passing in front of the tower”. EWEC 2008. Belgium.

[5] Bak, C (editor). Zahle, F. Sorensen, N. Madsen, H. “Research in Aeroelasticity”. Riso National Laboratory, Roskilde, Denmark. July 2008.

[6] Graham, J.M., Brown, C.J. “ROTOW Investigation of the Aerodynamic Interaction between Wind Turbine Rotor Blades and the Tower and its Impact on Wind Turbine Design.” EU Joule II Programme. Contract Nr. JOR3-CT98-0237 European Commission.

[7] Theodorsen, T. “General Theory of Aerodynamic Instability and the Mechanism of Flutter”. NACA Rep. 496, 1935.

Wind speed distributions in neutral atmospheres over homogenous terrain

Alfredo Peña

Wind Energy Department, Risø National Laboratory for Sustainable Energy, Denmark

ABSTRACT

Mixing-length and wind speed distributions are analyzed within the atmospheric boundary layer for neutral atmospheric conditions and homogeneous terrain from two different flat sites in Europe: the so-called “Leipzig wind profile”, and the “Høvsøre wind profile” where wind speed measurements were performed with a pulsed LiDAR up to 300 m, and compared well with cup anemometer observations. For both sites, the derived wind speed distributions deviate from the traditional model used within the surface layer, but compared well with the observations.

KEYWORDS

Atmospheric boundary layer, boundary-layer height, homogeneous terrain, LiDAR, mixing length, neutral atmospheres, wind profile

1 INTRODUCTION

Near-neutral wind speed profiles have been observed to deviate from the traditional logarithmic wind speed profile beyond surface layer−the lowest 10% of the atmospheric boundary layer (ABL)−over flat and homogeneous terrain [1, 2]. [2] described a wind speed profile model based on mixing-length theory which compared well with wind speed measurements up to 160 m over flat and homogeneous terrain at Høvsøre, Denmark, and over the North Sea [3]. In this paper, different mean wind speed distributions for the entire ABL−derived from several mixing-length models−are compared to the re-analysis data of the Leipzig wind profile in [1], and to combined cup anemometer and LiDAR measurements from a two months campaign at Høvsøre. The light detection and ranging (LiDAR) observations have previously shown high accuracy as demonstrated over land in [4] and over the sea in [3, 5].

2 MIXING-LENGTH AND WIND SPEED DISTRIBUTIONS

From mixing-length theory [6], the mean wind shear, $\partial U/\partial z$, is described by

$$\partial U/\partial z = u_*/\ell \tag{1}$$

alfredo.pena.diaz@risoe.dk

where U is the mean wind speed, z is the height above ground, u_* is the local friction velocity, and ℓ is the local mixing-length. The friction velocity is modelled in terms of the boundary-layer height, z_i, and its surface-layer value, u_{*o},

$$u = u_{*o}(1 - z/z_i) \tag{2}$$

The following mixing-length models are studied (Logarithmic [7], Blackadar 1 [8], Blackadar 2 [8], Lettau [9] and Gryning [2], respectively):

$$\ell = \kappa z \tag{3}$$

$$\ell = \kappa z/(1 + \kappa z C/(k_{b1} z_i)) \tag{4}$$

$$\ell = (k_{b2} z_i/C) \tanh(\kappa z C/(k_{b2} z_i)) \tag{5}$$

$$\ell = \kappa z/(1 + (\kappa z C/(k_l z_i))^{5/4}) \tag{6}$$

$$\ell = \kappa(1/z + 1/\ell_{MBL} + 1/(z_i - z))^{-1} \tag{7}$$

Integration of Eq. (1) from the surface roughness length z_o to the height z using the friction velocity model, Eq. (2), and the mixing-length models, Eq. (3)−(7), gives distributions of mean wind speed in the ABL which are compared against measurements taken during near-neutral conditions (Data) in Figure 1.

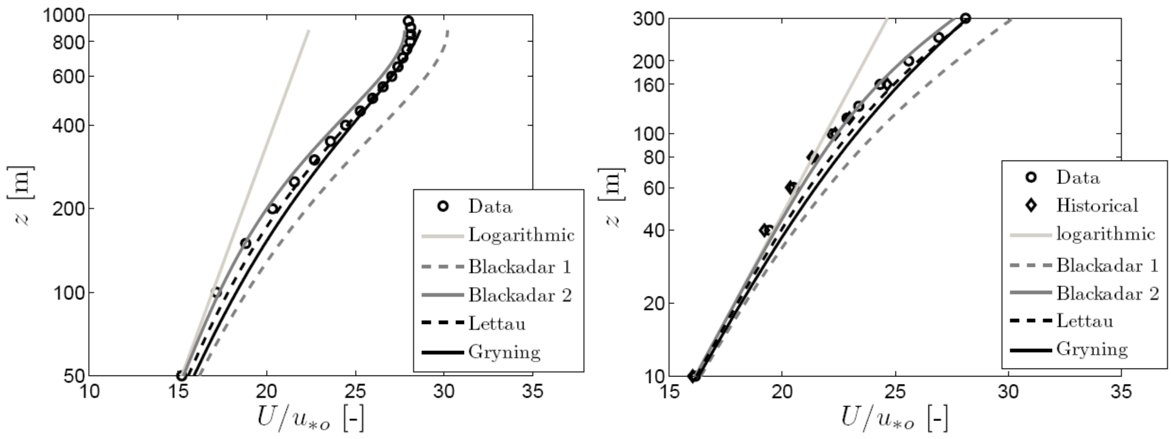


Figure 1: Mean wind speed distribution for the Leipzig (left) and the Høvsøre (right) wind profile. $\kappa = 0.4$, $z_0 = 0.11$ and 0.016 m, $z_i = 000$ and 760 m for Leipzig and Høvsøre, respectively, $C = 0.15$, $k_{b1} = 73$x10^{-4}, $k_{b2} = 58$x10^{-4}, $k_l = 100$x10^{-4}. The markers "historical" show the mean wind speed profile measured with the cup anemometers during 3.5 years.

3 CONCLUSIONS

Mean wind speed distributions, derived from several mixing-length models which account for the boundary-layer height, show good agreement compared to the Leipzig and the Høvsøre wind profiles. For both datasets, the traditional logarithmic wind speed profile underestimates the wind speed beyond surface layer.

Combined cup anemometer and LiDAR mean wind speed observations compare well with the historical mean wind speed profile at Høvsøre within the surface layer−the match is excellent using the scaling U/u_{*o}.

BIBLIOGRAPHY

[1] Lettau, H. (1950): A re-examination of the Leipzig wind profile considering some relations between wind and turbulence in the frictional layer. Tellus, 2, 125−129

[2] Gryning, S.-E., E. Batchvarova, B. Brümmer, H. Jørgensen, and S. Larsen (2007) : On the extension of the wind profile over homogeneous terrain beyond surface layer. Boundary-Layer Meteorol., 124, 251−268

[3] Peña, A., S.-E. Gryning, and C.B. Hasager (2008) : Measurements and modelling of the wind speed profile in the marine atmospheric boundary layer. Submitted to Boundary-Layer Meteorol.

[4] Mann, J, et al. (2008) : Comparison of 3D turbulence measurements using three staring wind lidars and a sonic anemometer. J. Phys. : Conf. Ser., 1, 012012 (6 pp)

[5] Peña, A, C.B. Hasager, S.-E. Gryning, M. Courtney, I. Antoniou, and T. Mikkelsen (2008) : Offshore wind profiling using light detection and ranging measurements. Wind Energy, in press.

[6] Prandtl, L (1932) : Metereologische Anwendung der Strömungslehre. Beitr. Phys. Atmos., 188−202

[7] Peña, A., and S.-E. Gryning (2008) : Charnock's roughness length model and non-dimensional wind profiles over the sea. Boundary-Layer Meteorol., 128, 191−203

[8] Panofsky, H. (1973) : Tower micrometeorology. In : Haugeb D.A. (ed) Workshop on micrometeorology. American Meteorology Society, pp 151−176

[9] Lettau (1962) : Theoretical wind spirals in the boundary layer of a barotropic atmosphere. Beitr. Phys. Atmos., 35, 195−212

High frequent wind fluctuations on wind turbine blades

Bernhard Stoevesandt[1], Joachim Peinke

[1] Forwind, Marie-Curie-Str. 1 26129 Oldenburg , Germany

ABSTRACT

Caused by disturbances at different scales, the wind is also highly turbulent at different time scales. The characteristics of the wind speed show strong intermittency effects at many different time scales. Even at time scales shorter than a second strong changes in wind speed can be observed.

Nevertheless for calculating loads of wind turbines, not only the changes in wind speed, but also in direction is important. So fluctuations in wind speed and direction and their coherence is being analysed by statistical means. Sonic measurments at hub hight of a 2MW wind turbine are being used to estimate the fluctuation intensity.

KEYWORDS

Windfield, intermittency, time scales, angle of attack

1 INTRODUCTION

The bases for the calculation of loads on a wind turbine is a good estimation of the expected wind field. Fluctuations in the wind speed or direction might lead to rapid changes in the angle of attack, which is part oft the concept of most blade element moment (BEM) theory programs to calculate aerodynamic properties for wind turbines. Nevertheless most wind field generators create a wind field based on a gaussian distributed wind speed, which leads to an underestimation of the fluctuations of the wind speeds (see [1]). Not only changes in wind speed cause aerodynamic trouble on wind turbines also the sudden changes in direction might lead to a changing angle of attack [2][3]. Therefore we investigate here the statistical properties of fluctuating wind.

2 WINDFIELD EVALUATION

2.1 Measurement Data

The measurement was taken in 60m hight from the ground using a sonic anemometer with a resolution of 50Hz. Here data of 7 continuous days in January 2005 were taken. The average windspeed during these days was $\bar{u}=6.94$ m/s, the average wind direction $\Theta=186.0°$.

Bernhard.stoevesandt@forwind.de

2.2 Wind fluctuations

The analysis of the changes in wind speed an direction on different time short time scales reveals strong intermittent behavior on the distribution of the increments of wind speed and

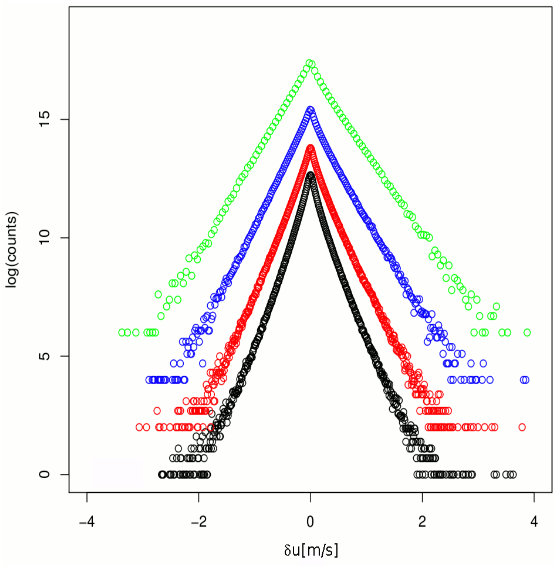


Figure 1: Log. distribution of the wind speed increments with change in wind speed in [m/s] at different time scales: 10 Hz (black), 5 Hz (red), 2 Hz (blue), 1 Hz (green). All show a significantly intermittent distribution. For visual reasons the upper distributions are ploted with an offset between 0 (black) and +6 (green).

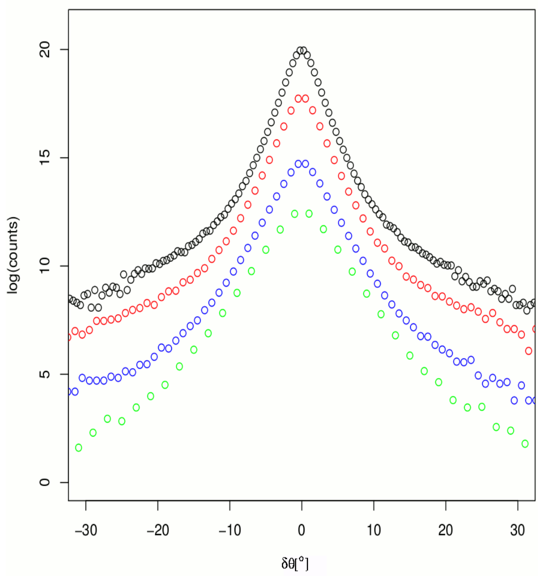


Figure 2: Log. distribution of the changes in wind direction in [°] within time sclaes from 1 to 10 Hz (coloring as in the left-hand figure). The distribution shows also tendency to occurances to stronger changes in wind direction, than a gaussian distribution would predict.

direction. The increments of the wind direction are calculated as described in [4]. The tendency to larger changes is even more distinct then for the changes in wind speed.

3 EFFECTS ON THE ANGLE OF ATTACK

In very short time periods a change in wind speed or direction will lead directly to changes in the angle of attack on the blade, as the controling of the wind turbines is not able to react so quickly to the changes. Changes in the wind direction lead to a varying change in the angle of attack since it depends on the position of the blade. Nevertheless the change in the wind direction is for a vertical blade directly “seen” as a change in the angle of attack.

4 CONCLUSIONS

At 60m hight the wind field showed a typical intermittend behavior of the wind speed distribution. The distribution of the changes in wind speed shows a similar behavior. Both effects can be observed on small time scales down to 0.1 seconds. This leads to rapid aerodynamics effects on wind turbine blades, which can be expressed in changes in the angle of attack.

BIBLIOGRAPHY

[1] Böttcher F., Barth S., Peinke J.: Small and large scale fluctuations in atmospheric wind speeds, Stoch. Environ. Res Ris. Assess. SERRA, 299 (2007)

[2] Sant, T., van Kuik, G. and van Bussel, G. J. W.: Estimating the Angle of Attack from Blade Pressure Measurements on the National Renewable Energy Laboratory Phase VI Rotor Using a Free Wake Vortex Model: Yawed Conditions, Wind Energ. 2008

[3] Shen W. Z., Hansen M. O. L., Sørensen J. N.: Determination of angle of attack (AOA) for rotating blades. In Proceedings of the Euromech Colloquium—-Wind Energy 2005. Peinke, Schaumann, Barth (eds). Springer: Oldenburg, Germany, 2006; 205–209.

[4] van Doorn, E., Drhuva, B., Sreenivasan K. R., Cassella, V.: Statistics of wind direction and its increments. Physics of Fluids, Vol. 12, No. 6 June 2000

Quasi-3D aerodynamic code for analyzing dynamic flap and sensor response

Néstor Ramos García[1]

1) Department of Mechanical Engineering, Fluid Mechanics Section, DTU, Denmark

ABSTRACT

In the project a fast and efficient quasi-3D aerodynamic code will be developed to analyze the local aerodynamic behaviour of an airfoil section of a wind turbine with a moving trailing edge flap and associated sensor response. The code will use the know concept of unsteady viscous–inviscid interaction via transpiration velocity. The inviscid calculations will be done by an unsteady potential flow panel method; meanwhile the viscous flow will be calculated using the quasi 3-D integral boundary layer equations. Simulations will be carried out for flow around an airfoil with a moving trailing edge of a static or rotating blade. These calculations will provide guidelines for designing and evaluating the Adaptative Trailing Edge Flap (ATEF) system on a wind turbine.

KEYWORDS

Moving flap, viscous-inviscid interaction, panel method, quasi 3-D integral boundary layer.

1 VISCOUS & INVISCID FLOW SOLVERS

1.1 Inviscid Solver

The Unsteady panel method solver is working with a uniform source distribution and a parabolic vortex distribution placed in the panel elements [1]. To satisfy the Kutta condition, the tangential velocities in the two elements beside the trailing edge are made equal. Wake is represented with 10 uniform vorticity distribution panel elements and (Nwake-10) point vortices, where Nwake is the total number of wake elements.

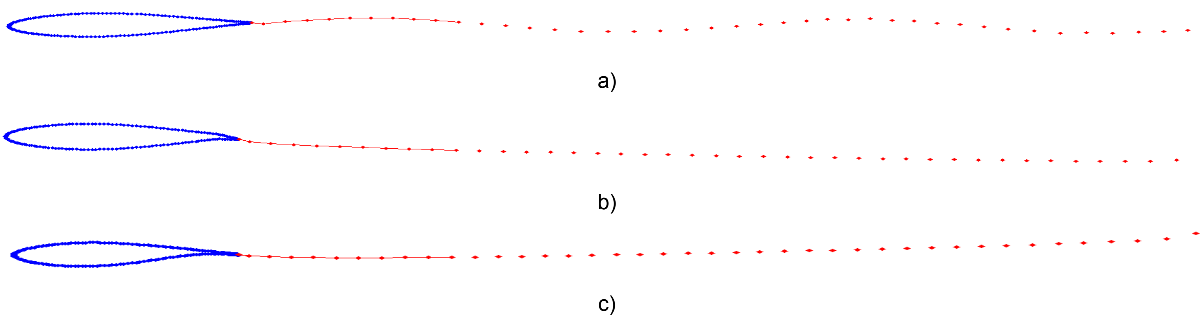


Figure 1: NACA63012a a) AoA=5.sin, b) AoA=0°, FlapAngle = -8°

c) Du91w2250 AoA = 7°

nrg@mek.dtu.dk

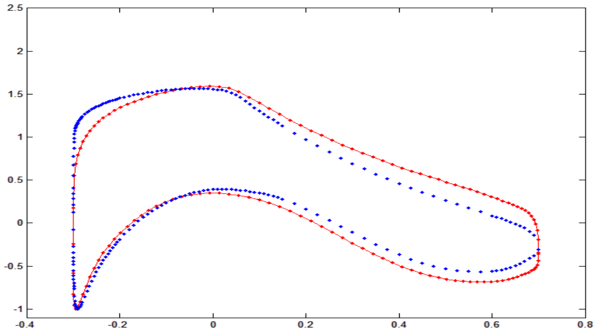


Figure 2: Airfoil: Du91w2250

AoA = 4°; --- Unsteady Panel Method --- Xfoil

For flow past a static Du91w2250 airfoil at an angle of attack of 7 degrees we obtain the following lift coefficient: Cl = 1.4372. This value is bigger than the lift coefficient computed with the Xfoil code inviscid mode: Cl = 1.4008. The pressure coefficient, Cp, for the Du91w2250 airfoil at 4° angle of attack is plotted in Figure 2. From the figure, we notice a good curve shape fitting compared with the Xfoil computations.

1.2 Viscous Solver

At the first stage of the viscous code, an integral boundary layer solver is based on solving the standard boundary layer integral momentum and kinetic energy shape parameter equations [2]. Following Drela [2], laminar and turbulent closure equations are used. For the laminar flow, the Falkner-Skan one-parameter profile family has been used to derive the closure relationships. Meanwhile, the turbulent closure relations are derived using the skin-friction and velocity profile formulas of Swafford [3]. A quasi 3-D integral boundary layer solver will be developed at the second stage of the project.

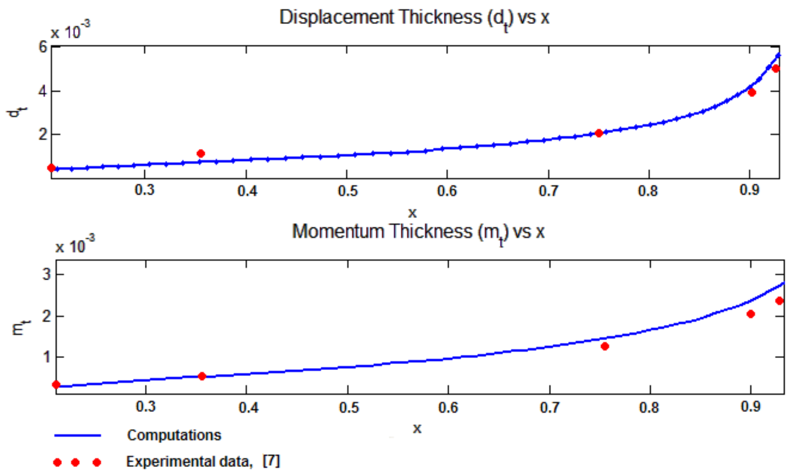


Figure 3: Upper surface boundary layer properties for the RAE 2822

Re = 5.7x10^6, AoA = 2.18°. Laminar / Turbulent 2D solver. First time step.

2 VISCOUS-INVISCID INTERACTION

The viscous-inviscid interaction is based on the assumption of an equivalent inviscid flow, where the effects of real flow can be added [4].

2.1 Transpiration velocity concept

The transpiration concept of the displacement effect was first introduced by Lighthill [5] in 1958.

$$W_{tw} = \frac{1}{\delta_{tw}} \frac{d}{ds} (\delta_{tw} \cdot U_{tw} \cdot \delta^*)$$

In order to displace the dividing streamline outwards the required distance δ* from the surface, the mass flow injected normal to the wall in the equivalent inviscid flow is chosen to be equal to the streamwise rate of change of the mass flow deficit [6].

The transpiration velocity will be used as input in the potential solver and will take into account the effects of the real flow in the inviscid panel method.

BIBLIOGRAPHY

[1] B.C. Basu and G.J. Hancock. *The unsteady motion of a two-dimensional aerofoil. J. Fluid Mech. (1978), vol. 87, part1, pp. 159-178.*

[2] M. Drela and M.B. Giles. *Viscous-Inviscid Analysis of transonic and low Reynolds number airfoils. AIAA Journal, Vol. 25, No.10, pp. 1347-1355.*

[3] T.W. Swafford. *Analytical approximation of two-dimensional separated turbulent boundary-layer velocity profiles. AIAA Journal, Vol. 21, June 1983, pp. 923-926.*

[4] V.A. Riziotis and S.G. Voutsinas. *Dynamic stall modelling on airfoils based on strong viscous-inviscid interaction coupling. Int. J. Numer. Meth. Fluids 2008; 56:185-208.*

[5] M.J. Lighthill. *On displacement thickness. J. Fluid Mech. 4, 383.*

[6] R.C. Lock and B.R. Williams. *Viscous-Inviscid interactions in external aerodynamics. Prog. Aerospace Sci. Vol. 24, pp 51-171, 1987.*

[7] D.L. Whitfield. *Integral Solution of compressible turbulent boundary layers using improved velocity profiles.*

Numerical Simulation of Dynamic Stall on a Wind Turbine Airfoil Using Spectral/Hp Methods

Medjroubi W. [1], Peinke J. [1], Stoevesandt B.[1]

[1] AG Hydrodynamik und Windenergie, Oldenburg University, Germany

ABSTRACT

The flow around airfoils is one of the most fundamental problems in aerodynamics. The challenging part of simulating this flow is the unsteady case, which results from flows at high incidence angles and during the transition from laminar to turbulent flow. The dynamic stall phenomenon is one important phenomenon associated with unsteady flows.

Wind turbines airfoils operating close to stall regimes are subject to high unsteady loads that can be of dramatic consequences on the life duration and the operating performance of the rotor. The prediction of the aerodynamic loads and moments is of great importance both from the theoretical and the practical aspect, and will permit a better understanding of the dynamic stall.

KEYWORDS

Dynamic stall, spectral/hp methods, computational fluid dynamics, low Reynolds number flows, flow over an airfoil.

1 INTRODUCTION

Above a certain critical value of the angle of attack, the flow around an airfoil (or any other lifting surface) develops what is called stall. If the airfoil is oscillating and the angle of attack is thus changing in an unsteady fashion, the stall is delayed to much higher angles than the static case. This phenomenon is called dynamic stall and is more severe and more persistent than its static counterpart. For the special case of wind turbines airfoils, characterisation of dynamic stall permits higher rotor efficiency and less structural vibrations. We present here the first results obtained from two dimensional simulations using a spectral/Hp methods to solve the unsteady, viscous Navier-Stokes equations.

2 NUMERICAL METHOD

2.1 THE METHOD

The numerical method is based on spectral element technique, which is fast convergent and allow the use of complex geometries. The method is based on the use of high-order spectral

wided.medjroubi@uni-oldenburg.de

expansions (Jacobi polynomials) and the decomposition of the physical domain in small volumes to describe the geometry. Details of the numerical method are described in [1]. To implement dynamic stall conditions we use two approaches. First approach; the inflow is under the form of a sinusoidal function, in which the frequency and the amplitude take different values. Second approach the airfoil it self is moving in heave in a sinusoidal fashion, which is accounted for using a moving frame of reference approach [2].

2.2 THE NUMERICAL CODE

We use a code that is an open source code, NekTar [3] which uses Galerkin and discontinuous Galerkin formulations and high-order trial basis. The algorithms and the numerical methods are described in [1].

3 NUMERICAL SIMULATION

We choose to simulate dynamic stall on a wind turbine profile, using an fx79-w15 profile. As stated before two methods are used to implement the dynamic stall conditions. Among the results which will be presented are two dimensional DNS at low to moderate Reynolds numbers (up to 10^3).

4 CONCLUSIONS

This paper deals with the direct numerical simulation of the unsteady flow over a wind turbine airfoil and the phenomenon of dynamic stall inherent to it.

BIBLIOGRAPHY

[1] Sherwin, S.J. & Karniadakis, G. E.: Spectral/hp Element Methods for Computational Fluid Dynamics, Oxford University Press, 1995.

[2] Sherwin, S.J. & Bearman P.W.: A moving frame of reference algorithm for fluid/structure interaction of rotating and translating bodies, International Journal for Numerical Methods in Fluids, vol. 38, 187-206, 2002

[3] www.nektar.info

Comparison of an actuator disc model with a full Rotor CFD model under uniform and shear inflow condition

Pierre-Elouan Réthoré[1,2], Niels Sørensen[1,2], Frederik Zahle[1], Jeppe Johansen[1]

[1] Risø DTU, Denmark [2] Aalborg University, Denmark

ABSTRACT

The goal set for this project is to compare qualitatively the wake features observed in two fundamentally different approaches to model the air flow around wind turbines. The comparison is carried on under two inflow conditions, one with a uniform profile, and one with a shear inflow. The main interest of this comparison is to gain knowledge from the level of details the actuator disc in comparison to the full rotor CFD model. This type of qualitative study can help to establish guidelines for using adequately the actuator disc model. A special focus is put on the wake rotational effect and its interaction with the shear in the near and far wake regions.

KEYWORDS

WIND TURBINE, ACTUATOR DISC, CFD, FULL ROTOR COMPUTATION.

1 INTRODUCTION

In order to validate engineering wind farm wake models, such as the one used in WAsP, more detailed CFD models can be used. The actuator disc model is appropriate for this task as it is possible to test the same assumptions made for designing the analytical models. But in order to rely on the result of the actuator disc model, it needs to be validated against even more detailed and realistic models, such as full rotor computations. The in-house CFD code of Risø DTU, EllipSys [1], is able to carry on full Rotor computations as well as actuator disc computation, which makes it particularly adapted for this comparison. The first steps of the comparison is to use the forces recorded during the full rotor computation as an input for the actuator disc model.

2 FULL ROTOR COMPUTATIONS

The full rotor CFD model resolves the actual blade and tower geometry of the wind turbine in the computational mesh. A full resolution of the boundary layer on the blades gives an

Pierre-elouan.rethore@risoe.dk

accurate estimation of the forces acting on the rotor as well as an accurate description wake expansion downstream the wind turbine. The model, developed by Zhale [2] us overset grid method to handle the relative movement between the rotor, tower and g boundary. A more detailed presentation of is found in [3].

3 ACTUATOR DISC MODEL

The actuator disc model is based on a discretization of the forces acting on the wind t blades, radially averaged over the rotor area. This eliminates the need to resolve the boundary layer, greatly reducing the size of the computational mesh. The discrete implementation in the Navier Stoke Equations is carried on by body forces compensa cell-face pressure jumps [4]. The forces assigned on the disc are extracted from tl Rotor CFD model.

4 FUTURE DIRECTIONS

Different assumptions are going to be tested using the actuator disc model, and com qualitatively with the full rotor computation such as ground modelling, wake ro turbulence model, different force distributions, different inflow definition (wind speed/dir shear).

The next milestone of the PhD is to compare wind farm data with a wind farm model actuator discs.

BIBLIOGRAPHY

[1] Sørensen N.N.. *General purpose flow solver applied to flow over hills*. Tec Report Risø-R-827(EN), Risoe National Laboratory, 1995.

[2] Zahle F., *Wind Turbine Aerodynamics Using an Incompressible Overset Grid M* PhD thesis, Imperial College, London, 2006.

[3] Zhale F., Sørensen N.N., *Rotor Aerodynamics in Atmospheric Shear* Proceedings EWEC 2008.

[4] Réthoré P.E., Sørensen N.N., *Actuator disc model using a modified Chow/SIMPLE pressure correction algorithm. Comparison with analytical sol* Proceedings EWEC 2008.

The Implementation of Variable Speed Wind Turbine Aerodynamic and Drive Train Modeling for Transient Analysis

Bing Liu

Department of Electrical Power Engineering, NTNU, Norway

ABSTRACT

This paper presents wind turbine aerodynamic and drive train modelling for the purpose of transient stability analysis using PSCAD. Firstly, a detailed aerodynamic and 2-mass drive train model are given numerically; secondly, a ready-to-use Fortran code is given for modelling implementation in PSCAD. Comparing with the standard wind turbine models in PSCAD, the presented model provide the possibility of setting the initialization condition, also can easily be extended or revised for other study purposes.

KEYWORDS

Variable speed, Wind Turbine, Modeling, PSCAD

1 INTRODUCTION

Accurate wind turbine mechanical parts models are essential for transient stability analysis. However, in the simulation tool PSCAD [1] ,the function of standard MOD2 type wind turbine component models is limited; for example, they don't provide the possibility of set the initial speed of both rotor and generator, which is necessary for some cases simulation. For this reason, the author has been working on the mechanical parts modeling, which can be easily revised for various study purpose.

Table 1: List of Symbols

Symbols	Notes	Symbols	Notes
P_{WT}	Mechanic power extracted	T_{em}	Generator electronic magnetic torque
A_{WT}	Wind turbine Rotor area	T_{gen}	Generator torque
ρ	Air density	T_{wtr}	Wind turbine shift torque
c_p	Power Coefficient	T_a	Aerodynamic torque
λ	Tip speed ratio	J_{gen}	Generator moment of inertia
θ	Pitch angle in degrees	J_{wtr}	Wind turbine moment of inertia
R	Rotor radius	K_{se}	Equivalent turbine shaft stiffness
V_W	Wind speed	N	Gearbox Ratio
Ω_{gen}	Generator mechanic speed	D_e	Equivalent turbine shaft damping
Ω_{wtr}	Turbine mechanical speed	D_{gen}	Generator damping constant

bing.liu@ntnu.no

2 WIND TURBINE MECHANIC PARTS MODELING

The model of wind turbine mechanic part is divided into two parts: blades model and drive train model. The aerodynamic torque extracted by blades is the interface between these two parts. The modeling processes are detailed as below.

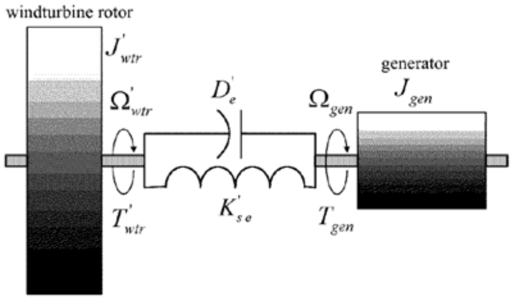


Figure 1: Equivalent diagram of wind turbine drive train looking on the generator side. [6]

2.1 Aerodynamic model

The aerodynamic model of wind turbine rotor is based on following well known algebraic equation, which gives the relationship between wind speed and the mechanic power extracted [5] [6].

$$P_{WT} = 0.5\rho A_{WT} c_p(\lambda,\theta) V_w^3 \quad (1)$$

The aerodynamic torque can be expressed by following equation:

$$T_a = 0.5\pi\rho R^2 V_w^3 c_p(\lambda,\theta) \quad (2)$$

As c_p is an un-linear function, a three-dimension look-up table was developed in respect with the variation of tip speed ratio and pitch angle, each specific wind turbine blades type has its own look-up table.

Furthermore, the wind speed can be set as constant value, or imported from files which containing real time wind speed data. If the wind speed value is less than cut-in speed or greater than cut-out speed, the aerodynamic torque will be set to zero, as the blades will be set to feather position under such situation.

2.2 Drive train Model

It is repeatedly argued that the damping effect of drive train gives significant oscillations to active power output; so the one mass drive train model is not accurate enough for transient stability analysis (See Akhmatov, Kunden and Nielsen, 2000). Most commonly, multi-mass drive train models are used. Furthermore, the gearbox and shaft inertia are relatively much more smaller than rotor generator inertia, which facilitate the possibility of two-mass model reduction by considering an equivalent system with equivalent stiffness and damping factor. Several lectures show that a two-mass keeps a good balance between the accuracy of transient analysis and complexity of model. The proposed two-mass structure drive train model is shown in Fig. 1. The drive train dynamic equations are [3]:

$$T_a - T_{wtr} = J_{wtr}\dot{\Omega}_{wtr} \qquad (3)$$

$$T_{gen} - T_{em} = J_{gen}\dot{\Omega}_{gen} \qquad (4)$$

And the shaft torque (written on generator side) can be expressed as below:

$$T_{wtr}^{'} = K_{se}^{'}\int(\Omega_{wtr}^{'} - \frac{\Omega_{gen}}{N})dt + D_e^{'}(\Omega_{wtr}^{'} - \frac{\Omega_{gen}}{N}) \qquad (5)$$

Where the whole drive train equivalent stiffness constant can be given by [6], which is similar as calculation of two parallel resistances.

$$\frac{1}{K_{se}^{'}} = \frac{1}{\frac{K_{wtr}}{N^2}} + \frac{1}{K_{gen}} \qquad (6)$$

According equations 3, 4, and 5 the dynamic equations of the drive train can be written as:

$$J_{gen}\dot{\Omega}_{gen} = -T_{em} - D_{gen}\Omega_{gen} - \frac{D_e}{N^2}\Omega_{gen} + \frac{D_e}{N}\Omega_{wtr} - \frac{K_{se}}{N}\int(\Omega_{wtr}^{'} - \frac{\Omega_{gen}}{N})dt \qquad (7)$$

$$J_{wtr}\dot{\Omega}_{wtr} = -T_a - D_e(\Omega_{wtr}^{'} - \frac{\Omega_{gen}}{N}) + K_{se}\int(\Omega_{wtr}^{'} - \frac{\Omega_{gen}}{N})dt \qquad (8)$$

It shall be mentioned that [7]: 'if the stiffness constant of low speed side is lower than the stiffness constant of high speed side, then the gearbox inertia need to be added into high speed side, and vice versa'.

3 MODELING IMPLEMENTATION IN PSCAD

To implement the upper mentioned modeling in PSCAD, the Fortran codes were given below for reference:

3.1 Aerodynamic model code:

```
! To calculate the aerodynamic torque extracted
SUBROUTINE aerodynamic (cut_in, cut-out, Radius, Lambda, Wwtr, Wwtr_pu, Vw, Phi,&
& Beta, P_n,Ta_pu)
! Include the Fortran standard statements
! Define the variables
! Define the cp look up table Function
! Calculate Lambda
        Lambda = Radius * Wwtr / Vw
! Load cp value from the look-up table
! Calculate the aerodynamic torque Pwt
        Pwt = 0.5* PI_ * Phi * Radius * Radius * Vw * Vw * Vw * cp
        IF (Vw .GT. cut_in) .AND. (Vw .LT. cut_out ) THEN
! Calculate torque to per unit
        Ta_pu = - Pwt / P_n / 1000000 / Wwtr_pu
```

```
ELSE
        Ta_pu =0
ENDIF
        RETURN
        END
```

3.2 Drive train model code:

```
   SUBROUTINE drive_train(Wwtr, P_n , Wgen_n, N, Kse, Tem, Tem_pu ,De,  Jwtr,Jgen,
&Wgen_pu, Wwtr_pu)
! Include the Fortran standard statements
! Define the variables
! To calculate the shaft angular velocity
        Wwtr  = Wgen_n / N * 2 * PI_/60
! To calculate the generator angular velocity
        Wgen = Wgen_n * 2 * PI_/60
! To calculate the angular difference
        Omega = -Ta*( P_n *1000000)/( Wgen2*PI_/60/N) / Kse
! To calculate the angular velocity difference
        Delta_Omega = (Wwtr - Wgen /N)
! To calculate generator electronic magnetic torque
Tem_pu = -Tem * (P_n *1000000)/( Wgen *2*PI_/60)
! To calculate Ta_> wind turbine aerodynamic torque
Ta_pu = -Ta * (P_n *1000000)/( Wgen *2*PI_/60)
! To calculate turbine shift torque
        Twtr = Kse * Omega + De * Delta_Omega
! To calculate the new turbine rotor angular velocity
        Wwtr = Wwtr + ( Ta_pu - Twtr) / Jwtr * DELT
! To calculate the new generator angular velocity
Wgen = Wgen + ( Twtr / N - Tem_pu) / Jgen * DELT
! To calculate the new angular difference
        Omega = Omega + Delta_Omega * DELT
! To calculate new turbine rotor angular velocity / PU
        Wwtr_pu = Wwtr  * 60 / 2 / PI_ * N / Wgen
! To calculate the new generator angular velocity / PU
        Wgen_pu = Wgen  * 60 / 2.0 / PI_ / Wgen
        RETURN
        END
```

4 CONCLUSIONS

This paper deals with wind turbine aerodynamic and drive train modeling for the purpose of transient stability analysis using PSCAD, the numerical presentation and Fortran code detailed here can be significant reference for further extension.

BIBLIOGRAPHY

[1] PSCAD® / EMTDC™ online help.

[2] M. Hogdahl and J. G. Nielsen, “Modeling of the Vestas V80 VCS wind turbine with lowvoltage ride-through,” in Proc. 5th Int.Workshop Large-Scale Integration Wind Power Transmission Networks Offshore Wind Farms, Glasgow, U.K., Apr. 7–8, 2005

[3] Modeling and control of variable-speed wind-turbine drive-system dynamics, Novak, P. Ekelund, T. Jovik, I.Schmidtbauer, B. Control Eng. Lab., Chalmers Univ. of Technol., Goteborg, Sweden; Control Systems Magazine, IEEE, Aug. 1995

[4] Stability Simulation Of Wind Turbine Systems, Anderson, P.M.; Bose, A.; IEEE Transactions on Power Apparatus and Systems, Volume PAS-102, Issue 12, Dec. 1983 Page(s):3791 – 3795

[5] Wind Power In Power Systems, edited by Thomas Ackermann; Wiley 2005; 691 pp, ISBN 0-470-85508-8

[6] Wind turbine blockset in matlab simulink, Aalborg University, Institute of Energy Technology, RISØ, http://www.iet.aau.dk/Research/research_prog/wind_turbine /Projects/SimPlatformPrj/htm_files/Project.htm

[7] Comparative study on transient stability analysis of wind turbine generator system using different drive train models, Muyeen, S.M& Others; Renewable Power Generation, IET, Volume 1, Issue 2, June 2007

Dynamic loads on a wind turbines rotor

Tanja Mücke, Joachim Peinke

ForWind – Center for Wind Energy Research, Oldenburg, Germany

ABSTRACT

Turbulent wind fields are normally simulated with models using purely Gaussian statistics. Describing the turbulence with the statistics of the velocity increments, it can be seen that in experimentally measured wind fields the statistics are not Gaussian but intermittent.

Under application of the program FAST with the embedded subroutines of AeroDyn, we use the blade element-momentum theory to calculate the dynamic loads on a wind turbines rotor blade plane for different wind inflows. The results from intermittent turbulent flows will then be compared to those from Gaussian wind fields (IEC-Norm).

KEYWORDS

Loads, wind turbine, blade element momentum theory, intermittent wind fields, statistics.

1 INTRODUCTION

During a wind turbines design process the turbulent wind fields are normally simulated according to the IEC Standard 61400-1. In the standards, different simulation methods are described. All these models are using purely Gaussian statistics.

To get time-resolved information about a fluctuating wind field u, the statistics of velocity increments u_τ with

$$u_\tau = u(t+\tau) - u(t). \tag{1}$$

can be used. Describing the turbulence with the statistics of the velocity increments, it can be seen that in experimentally measured wind fields the statistics are not Gaussian but intermittent [1]. The intermittent distributions of atmospheric velocity fluctuations are characterized by marked fat tails and a peak around zero. The increments directly measure the velocity difference after a characteristic time τ. That means more extreme velocity fluctuations occur in the measured wind fields than in the simulated Gaussian one. We expect that this higher quantity of extreme events leads to larger alternating load changes on the airfoil.

tanja.muecke@forwind.de

2 NUMERICAL SIMULATIONS

Under application of the program FAST [2] with the embedded subroutines of AeroDyn [3], we use the blade element-momentum theory to calculate the dynamic loads on a wind turbines rotor blade plane for different wind inflows. The results from intermittent turbulent flows will then be compared to those from Gaussian wind fields (IEC-Norm). An example of the resulting torque increments, as measure of the alternating loads, for these two different flows is shown in Figure 1.

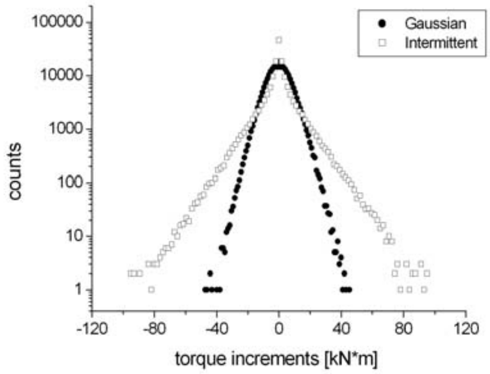


Figure 1: Observed frequency of rotor torque increments after the time $\tau = 1$ sec under the influence of Gaussian and intermittent turbulent flows. The resulting torque shows more extreme fluctuations by an intermittent inflow than by a Gaussian one.

Furthermore, we calculate the loads for measured turbulent wind data. The analysed wind fields were recorded during January 1984 and February 1987 at the site of the GORWIAN wind turbine [4]. The high-frequented turbulent wind data were measured in a grid of 100 m x 76 m.

BIBLIOGRAPHY

[1] F. Böttcher, St. Barth and J. Peinke, On the statistics of wind gusts, Bound.-Layer Meteor., 108:163-173, 2003.

[2] FAST by Jason Jonkman, NWTC Design Codes, http://wind.nrel.gov/designcodes/simulators/fast/. Last modified 12-August-2005; accessed 12-August-2005.

[3] AeroDyn v12.58 by Dr. David J. Laino, NWTC Design Codes, http://wind.nrel.gov/designcodes/simulators/aerodyn/. Last modified 05-July-2005; accessed 05-July-2005.

[4] H. Günther, B. Hennemuth, Erste Aufbereitung von flächenhaften Windmessdaten in Höhen bis 150 m, DWD BMBF-Projekt 0329372A, 1998.

SESSION 2-C
SOCIAL AND BEHAVIORAL ASPECTS

(Parallel to the Session 2-A)

Wednesday, 01.10.2008

16:00 – 16:40

Building 22A / Room 020

Supervisor:

Prof. M. Geir, NTNU

Chairman:

H. S. Toft, Aalborg University

Public Acceptance and Wind Energy Plants - an Environmental Psychological Consideration

Dipl.-Psych. Jan Zoellner

Otto-von-Guericke-University Magdeburg; Department of Psychology; Germany

ABSTRACT

Using an environmental psychological approach, it is aimed at eliciting the relevant social factors to the formation of public acceptance towards wind energy and to further develop the understanding and definition of acceptance.

A case-comparison study of three different German counties was made to research social processes during the implementation process of wind energy plants. In order to address the complexity of the topic the study has been conducted in a multi-modal research design. As a matter of principle, a strong connection between the economical estimation and a reported public acceptance towards the wind turbines became evident.

Furthermore, the consideration of procedural justice criteria during the planning and installation process such as transparency, early and accurate information as well as possibilities to participate were important influencing factors.

KEYWORDS

Psychological Approach, Public Acceptance, Planning Strategies

1 INTRODUCTION

The present contribution addresses the public acceptance of wind energy plants from a socio-scientific perspective, a topic which has been insufficiently documented so far. Due to the increasing need for alternative energy production systems during the last decade the number of wind energy plants has risen rapidly. In this context, it is fair to state that renewable energy systems (RES) are playing a central role to achieve climate protection goals set by environmental policies. In Germany, power generation using renewable energies has been particularly strong supported by the Federal Government. As a result, Germany has become a global player in this sector. However, this high degree of renewable energy utilisation and wind energy in special is not undisputed in Germany. Main arguments in the current debate concerning the utilisation of wind energy plants are the changes of the landscape and potentially increasing energy costs [1].

Jan.zoellner@ovgu.de

While in some regions citizens form initiatives against wind energy plants on local levels because they feel the long-distance visible wind turbines to be a physical, mental and aesthetical burden, other communities apply for leasing their land to investors.

2 METHOD

Even though representative public opinion polls show support for a progressive energy policy as well as for a growing part of renewable energies in power generation as a matter of principle, many residents feel severely limited in their quality of life by the nearby installed renewable technology plants.

Therefore, a case-comparison study of three different German counties was made to identify relevant social factors for the implementation of wind energy plants [2]. In order to address the complexity of the topic the study has been conducted in a multi-modal research design. Within this approach, the main focus is on the social dynamics during the implementation process. What are the psychological determinants that make residents reject wind energy projects and at which stage do residents decide to get involved actively, e.g. form up a local initiative?

To answer these questions, a standardised questionnaire was used. For this purpose, important topic complexes were operationalised according to underlying psychological theories in several scales. The present study opted for a design geared to include as many aspects of the issue “wind turbines” as possible, for example the general attitude towards RES, economical estimation, risk evaluation, perceived procedural justice during the implementation process, perceived changes of the landscape. In addition, several interviews with key persons were applied.

3 CONCLUSIONS

As a matter of principle, a strong connection between the economical estimation and a reported public acceptance towards the wind turbines became evident. The residents and communities want to participate also in terms of economical profits instead of just bear the costs like changes of the landscape or a worried noise disturbance. This perceived benefit from the installation of wind turbines can be set on different levels: for the respective person itself, for the community and for the state (national economy) as a whole. Besides material (financial) benefits, there can also be immaterial benefits like a more positive feeling in the region because of RES utilization or a better image of the region.

Furthermore, the consideration of procedural justice criteria during the planning and installation process such as transparency, early and accurate information as well as possibilities to participate were important influencing factors. By this means the perceived procedural justice became evident as a conflict factor of particular importance.

Especially the administrative zoning, planning, and licensing procedures were often perceived as rather unjust. Moreover, residents criticise that their interests are not represented by local politicians, particularly when compared to economic interests. In consequence a large number demands to have a voice in future. This result is congruent with results of previous studies [3, 4].

All in all, the central conclusion of the project concerning the public acceptance of wind turbines is that one success factor is to focus not only on technological, legal end economical issues, but also on social processes.

BIBLIOGRAPHY

[1] Zoellner, J. & Schweizer-Ries, P. (in review). Wind Energy Plants and Perception of the Landscape – an Environmental-Psychological Consideration.

[2] Project funded by the German BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety): “Acceptance of Renewable Energies and Socio-scientific Questions”. Homepage: www.uni-magdeburg.de/upsy/akzeptanz

[3] Zoellner, J., Ittner, H. & Schweizer-Ries, P. (2005). Perceived Procedural Justice as a Conflict Factor in Wind Energy Plants Planning Processes 5th BIEE. Paper presented at the Academic Conference "European Energy - Synergies and Conflicts", St. John's College Oxford, 22.-23.09.2005.

[4] Villalobos Montoya, C. & Schweizer-Ries, P. (2006). Rural solar energy supply and participation – the example of a small Hellenic community. C. Arcidiacono & H. Legewie (Eds.). Learning Communities and Sustainable Social-economic City Development. Proceedings of the 5thEuropean Congress for Community Psychology Social Responsibility in a Globalizing World (54-65), Berlin, Sept. 16-19, 2004.

Mental Models in technical development cooperation – exemplary analysis of rural electrification with solar home systems

Annika Tillmans

Otto-von-Guericke-University Magdeburg, Germany

ABSTRACT

For real participation as a key to successful implementation of solar home systems (SHS) in developing countries stakeholders need a set of relevant meta-competencies like the ability to take the user's perspective and the ability for systemic sociotechnical thinking. The analysis of the mental models held by stakeholders and users about the connection between humans, technology and implementation process of SHS will help to identify, whether stakeholders view humans as a relevant part of the technical innovation and if they are able to anticipate the user's view of the system.

KEYWORDS

Mental Models, solar home systems, perspective-taking, socio-technical design

1 INTRODUCTION

Participation is a key for successful development cooperation and for sustainable technology implementation in rural areas in developing countries [1], [2], [3]. Relevant meta-competencies for stakeholders in development cooperation to promote real participation are the ability to take the perspective of potential users of SHS and the ability for systemic socio-technical thinking, i.e. the awareness that technical equipment cannot be considered as detached from the people using it. Only if these meta-competencies exist, stakeholders can be aware that actual user's needs may be very different from "experts" expectations. Current education of staff in developmental cooperation does not focus sufficiently on taking perspective and socio-technical thinking.

2 MENTAL MODELS

Mental models are an interesting tool to analyze these meta-competencies: stakeholder's and user's concepts of the connection between human, technology and process in implementation of SHS can be described as mental models. All logic inferences, e.g. about

annika.tillmans@ovgu.de

cause and effect or possibilities to act are determined by this mental model [4]. Stakeholders may construct and implement the SHS according to a very technically oriented model, while the user's mental model during use and maintenance of the system may be very different.

3 QUESTIONS

Are stakeholders in rural electrification able to think in a socio-technical way? Is their way of working characterized by systemic socio-technical thinking and perspective taking? What kind of mental models exist in user's and stakeholder's minds about SHS? Are stakeholders able to anticipate user's mental models? Which aspects in the stakeholder's biography and education contribute to this ability? Did the training for their current task make a contribution? Which aspects of stakeholder's professional biography should be integrated in future education of staff in developmental cooperation? What kind of conclusions can be drawn for the actual planning, realization and evaluation of electrification projects?

4 METHODS

Two programs of rural electrification in different stages of realization will be analyzed. The current idea is to compare the work of Grameen Shakti in Bangladesh as an example for best practice with another project (maybe the program of the Evangelical Social Action Forum in India which is still underway), which may face problems in perspective taking and socio-technical thinking.

The main method of investigation will be the expert interview [4] with stakeholders including biographical questions which will be analyzed on the basis of Grounded Theory [6]. Additionally manuals of education programs for stakeholders will be evaluated.

To approach the question of mental models a network of the interview partner's concept of SHS will be developed in dialogue-consensus-technique [7]. In this way ideas or images can be made visible and comparable. In the same way the stakeholder's idea of the user's mental models will be recorded.

Of course the user's mental models themselves will also be analyzed. It is planned to develop the same kind of network with them in dialogue-consensus, but maybe by talking to a whole group of villagers as a more culturally adapted method. In a participating observation people will be watched while using their SHS [8]. Additionally users will be asked to draw or take pictures to illustrate the symbolic meaning of SHS [9].

Finally a comparison will be made between the by stakeholder's expected mental models and the actual user's models and shown if there is a higher matching in Grameen Shakti's project than in the project of comparison.

BIBLIOGRAPHY

[1] De Laet, M. & Mol, A. (2000).The Zimbabwe Bush Pump: Mechanics of a Fluid Technology. *Social Studies of Science*, 30, 2. S.225-263.

[2] Clemens, B., Karp, A.W. & Papadakis, M. (2002). The People’s Water: Technology Transfer and Community Empowerment in Guatemala. Zeitschrift: Knowledge and Society, Bd. 13, S.105-127.

[3] Schweizer, P. (1996). Psychologische Faktoren bei der Nutzung regenerativer Energien: Eine Studie zum Einsatz von Solartechnik im zentralen Himalaya. Aktuelle Psychologische Forschung (Bd. 19). Lengerich: Pabst.

[4] Anderson, J.R. (1996). Kognitive Psychologie. Heidelberg: Spektrum.

[5] Mieg, H.A. & Brunner, B. (2001). *Experteninterviews* (MUB Working Paper 6).

[6] Strauß, A. & Corbin, J. (1996). Grundlagen Qualitativer Sozialforschung. Weinheim: Beltz Psychologie Verlags Union.

[7] Scheele, B. & Groeben, N. (1988). Dialog-Konsens-Methoden. Zur Rekonstruktion subjektiver Theorien. Tübingen: Francke.

[8] Lüders, C. (2003). Beobachten im Feld und Ethnographie. In: Flick, U., Kardorf, E.v. & Steinke, I. (Hrsg.). Qualitative Forschung. Ein Handbuch. 2. Aufl., S. 384-401, Reinbek: Rowohlt Taschenbuch Verlag.

[9] Devine-Wright, H. (2007). Vortrag im Rahmen der 7th Biennial Conference on Environmental Psychology: An exploratory study of social representations of electricity network technologies.

SESSION 3-A
SIMULATION AND MODELLING – PART III

(Parallel to the Session 3-B)

Thursday, 02.10.2008

09:30 – 11:40

Building 22A / Room 021 (H2)

Supervisor:

Dr. D. Heinemann, ForWind, University of Oldenburg

Chairman:

A. Pena, Risø

Distributed Actuation, Sensing, and Control of Flexible Wind Turbine Blades

Justin K. Rice[1], Michel Verhaegen[2]

[1,2] Delft Center for Systems and Control, The Netherlands

1 Abstract

As wind turbines continue to increase in size and flexibility, blade-vibration induced fatigue loading will become more important for design, and more difficult to control using pitch actuation and sensing alone. To remedy this, the 'smart blade' concept, with sensors and actuators distributed along span of the blade, has been suggested. We investigate the advantages of this proposal.

KEYWORDS: Flexible Blades, distributed control, sensor networks

2 Introduction

In recent years, wind turbines have been getting larger and more flexible [7][10][5]. The move offshore will make this even more so, and simultaneously make fatigue strains even more important, as service costs increase. To deal with these issues, people have been proposing the 'smart rotor' concept. Different concepts, actuators, and methods of design have been discussed and tried in the literature with various demonstrated benefits [2][12][1][4][11] see [3] for an overview. However, to our knowledge there has not been sufficient investigation into how to best take advantage of it using feedback control.

Analysis of large scale or infinite dimensional systems is inherently difficult. It has been shown that even simple infinite dimensional linear models can exhibit complex and unexpected behavior, for example, the *linearized* Navier Stokes equations in [6] have been shown to show streaking and other characteristics of turbulence formerly only believed to be a nonlinear phenomenon. Control of such systems is even more complicated; classical control methods are ill-equipped to deal with infinite states, and low-order model reductions may be numerically infeasible for very large dimensional heterogeneous systems.

In actual wind turbine design, the real objective that one would ideally minimize is cost/kWh over the life of the turbine, taking into account manufacturing cost, maintenance, gross power production, power quality, and ultimately disposal. However, such considerations are too complicated for us, so we will restrict ourselves to consideration of some of the immediately measurable quantities on the wind turbine itself. We also don't need a complicated model to illustrate these fundamental methods, so for transparency and brevity we will use the simplest blade model possible, a Bernoulli beam.

3 Beam model & Discretization

We will consider a single rotor blade modeled as a Euler-Bernoulli beam with only a flap-wise degree of freedom, and viscous but not strain damping.

$$\rho(r)\frac{\partial^2 s(r,t)}{\partial t^2} + \gamma(r)\frac{\partial s(r,t)}{\partial t} + \frac{\partial^2}{\partial r^2}\left(E(r)I(r)\frac{\partial^2 s(r,t)}{\partial r^2}\right) = F_u(r,t) + F_d(r,t)$$

and with clamped-free boundary conditions:

$$s(0,t) = \frac{\partial s}{\partial r}(0,t) = EI(L)\frac{\partial^2 s}{\partial r^2}(L,t) = \frac{\partial}{\partial r}\left(EI(r)\frac{\partial^2 s}{\partial r^2}(r,t)\right)(L) = 0$$

where $r \in [0, L]$ is the spanwise position along the blade from the clamped root ($r = 0$) to the free tip($r = L$), $s(r,t)$ is the displacement in the flapwise direction, ρ is the linear density, γ is the viscous damping constant, EI is the bending stiffness, and F_u and F_d are the control and disturbance linear force intensity inputs, respectively. After some simplifying assumptions(for the sake of brevity) the above equations can be re-arranged into an infinite dimensional state space form:

$$\begin{bmatrix}\dot{s}\\ \ddot{s}\end{bmatrix} = \begin{bmatrix} 0 & I \\ -\frac{EI}{\rho}\frac{\partial^4}{\partial r^4} & -\frac{\gamma}{\rho}\end{bmatrix}\begin{bmatrix}s\\ \dot{s}\end{bmatrix} + \begin{bmatrix}0\\ F_u(r)\end{bmatrix} + \begin{bmatrix}0\\ F_d(r)\end{bmatrix} \quad (1)$$

J.K.Rice@tudelft.nl

with boundary conditions:

$$s(t,0) = \frac{\partial s}{\partial r}(t,0) = 0, \qquad \frac{\partial^2 s}{\partial r^2}(t,L) = \frac{\partial^3 s}{\partial r^3}(t,L) = 0 \tag{2}$$

3.1 Measurements & Actuators & Disturbances & Costs

In the following, since they are the most widely currently employed, we will consider sensors that output strain measurements, although our framework would work also using accelerometer data and flow data, were we to include aerodynamic components in our model. Our measurements, $y(r,t)$ will thus be of the form:

$$y = p(r)\frac{\partial^2 s}{\partial r^2} + n(r,t) \tag{3}$$

where $p(r)$ is some sensor constant and $n(r,t)$ is random measurement noise.

Actuators that have been recently considered for application to wind turbine blades include trailing edge piezo-actuated flaps, gurney flaps and microtabs, Synthetic Jet actuator and its derivative the 'directed synthetic jet', and the Coanda jet-flap(see [3] for an overview).

While each of these actuators has a different working mechanism and different properties, they all work fundamentally by changing the local coefficient of lift of the airfoil, and thus the local lift force. Hence in the following we will consider a generic 'force actuator'(as opposed to a moment actuator, such as a piezo-patch) which will approximate any of the above actuators for the smart blade:

$$F_u^{smart}(r) = b_p(r)g(s)u_{smart}(r) \tag{4}$$

where $b_p(r)$ is some constant relating the local change in coefficient of lift to the input effort u, and $g(s)$ is a transfer function representing the internal dynamics of the actuator.

To keep our model simple, we will not incorporate any detailed disturbance model knowledge, and will just assume our disturbances to be bounded, with the following term in the state equation: $F_d = d(r)$.

To heuristically minimize fatigue damage, our cost function will be a sum of strain and 'strain velocity' components:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} p_{z_1}(r)\frac{\partial^2}{\partial r^2} & 0 \\ 0 & p_{z_2}(r)\frac{\partial^2}{\partial r^2} \end{bmatrix} \begin{bmatrix} s \\ \dot{s} \end{bmatrix} \tag{5}$$

Minimizing the 'strain velocity' should damp the high frequency oscillatory modes, and decrease the number of strain oscillations in the closed loop, thus decreasing the damage intensity.

3.2 Discretization

While technically correct, the system model equations as we have shown them in (1), (3), (4), (5) are not actually very useful for analysis and design. The state, input, and output variables x, u, y, z are all on infinite dimensional Hilbert spaces, and some of the infinite dimensional operators are heterogeneous and even unbounded, making computations quite difficult. To treat this problem, we will thus approximate all of the equations using a finite difference discretization.

We divide the function spaces $s : \mathcal{L}_2[0, L]$ into a finite number $(N)$of points, $\overline{s} = [s_1, s_2, s_3...s_N]^T$ and approximate the spatial partial derivatives using some finite difference 2nd order Taylor series expansions[9](although higher order would also fit into our framework).

4 SSS controller synthesis

Once the derivatives have been approximated on a Euclidean space using finite difference, it has recently been shown that an equivalent 'interconnected subsystem model' can be formed, leading to a state space realization with 'Sequentially Semi-Separable'(SSS) structure[8]. This special matrix structure can then be exploited for computationally efficient, structure preserving arbitrarily non-conservative sub-optimal controller synthesis, and the resulting controller with an SSS state space realization may be 're-distributed' along the same interconnection topology as the original system, allowing an efficient and practical implementation(see Fig 1). Our future research will investigate precisely the benefit of such controller implementations, and the advantages over other actuator configurations, such as tip control or pitch control systems.

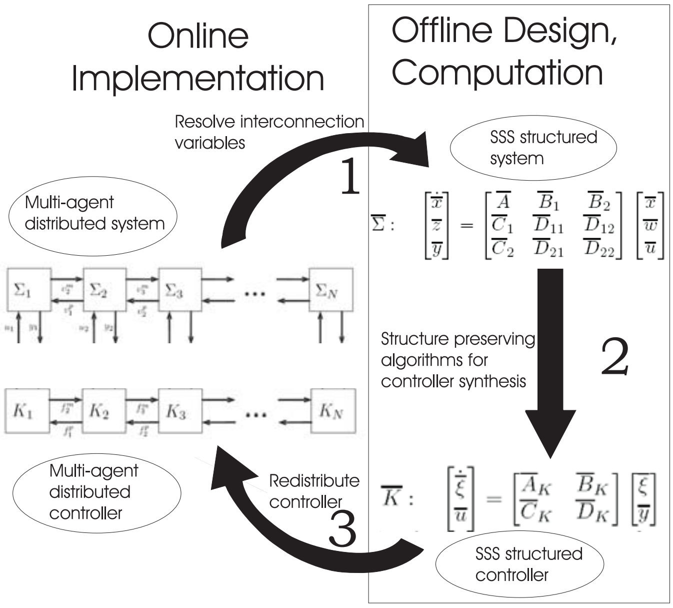


Figure 1: Conceptual diagram of SSS distributed control synthesis

References

[1] Peter B. Anderson, Mac Gaunaa, Christian Bak, and Thomas Buhl. Load alleviation on wind turbine blades using variable airfoil geometry. *European Wind Energy Conference*, 2006.

[2] Nengsheng Bao, Haoming Ma, and Zhiquan Ye. Experimental study of wind turbine blade power augmentation using airfoil flaps, including the gurney flap. *Wind engineering*, 24:25–34, 2000.

[3] T.K. Barlas and G. A. M. van Kuik. State of the art and prospectives of smart rotor conrol for wind turbines. *The Science of Making Torque from Wind, Journal of Physics: Conference Series*, 75, 2007.

[4] Thomas Buhl, Christian Bak, Mac Gaunaa, and Peter B. Anderson. Load alleviation through adaptive trailing edge control surfaces: Adapwing overview. *European Wind Energy Conference*, 2006.

[5] C.P. Butterfield, W. Musial, and J. Jonkman. Overview of offshore wind technology. *NREL preprint*, 2007.

[6] Mihailo Jovanovic and Bassam Bamieh. The spatio-temporal impulse response of the linearized navier-stokes equations. *proceedings of the ACC*, pages 1948–1953, 2001.

[7] D.C. Quarton, Garrad Hassan, and Partners Ltd. The evolution of wind turbine design analysis–a twenty year progress review. *Wind Energy*, 1:5–24, 1998.

[8] Justin K. Rice and Michel Verhaegen. Distributed control: A sequentially semi-separable approach for heterogeneous linear systems. *IEEE Trans. Autom. Control*, Accepted for Publication, temporarily available at http://www.dcsc.tudelft.nl/∼jrice/Publications.htm.

[9] John C. Strikwerda. *Finite Difference Schemes and Partial Differential Equations*. Wadsworth Publ. Co, 1989.

[10] R. Thresher and A. Laxson. Advanced wind technology: New challenges for a new century. *proceedings of the EWEC*, 2006.

[11] Chanin Tongchitpakdee, Sarun Benjanirat, and Lakshmi N. Sankar. Numerical studies of the effects of active and passive circulation enhancement concepts on wind turbine performance. *Journal of Solar Energy Engineering*, 128:432–445, 2006.

[12] J.R. Zayas, C.P. van Dam, R. Chow, J.P. Baker, and E.A. Mayda. Active aerodynamic load control for wind turbine blades. *proceedings of the EWEC*, 2006.

Model Predictive Control of a Floating Wind Turbine

L. C. Henriksen A[1], N. K. Poulsen[2]

[1] Risø DTU, Denmark, [2] DTU Informatics, Denmark

ABSTRACT

In this paper control a floating wind turbine inspired by the Hywind concept is presented. First principle equations for the floating wind turbine are used for a mathematical model. An analysis discussing the differences between normal and floating wind turbines is performed. The derived model is used in a model-based control regime, known as or model predictive control. The model predictive controller is able to handle constraints on various states and succeeds in controlling the floating wind turbine with satisfactory results.

KEYWORDS

Model Predictive Control, Constraints, Floating Wind Turbine, Pitch and Generator Torque Control

1 INTRODUCTION

Floating wind turbines have become a research area of increasing interest as the sites for offshore wind turbines founded on the sea bed are rapidly being occupied by emerging wind farms. Different configurations of floating wind turbines have been developed through the last years among these projects are Blue H, SWAY and Hywind [1-3].The floating wind turbine presented in this paper is inspired by the Hywind concept. The Hywind concept is initially based on a regular offshore wind turbine mounted on a floating hull. The floating hull is a submerged vertical concrete cylindrical structure with a height of about 120 meters, which is fastened to the sea bed with 3 mooring lines. Model predictive control (MPC) offers the ability to handle constraints and is used to honor the constraints on the actuators, i.e. pitch angle and -rate and torque and –rate. MPC has previously been investigated with application on wind turbines in [4,5]. This paper gives a brief presentation of the work already achieved and the work ahead concerning MPC of floating wind turbines.

2 FLOATING WIND TURBINE

The wind turbine is modelled with a simplified structural model and a steady state aero-dynamic model. The structural model includes flexibility in drive train and tower fore-aft motion.

lars.christian.henriksen@risoe.dk

Figure 1: Floating wind turbine based on the Hywind concept [6].

To simulate the floating nature of the wind turbine the tower foundation stiffness of the floating wind turbine is significantly lower than that for standard onshore wind turbines. The aerodynamic model is based BEM and look-up tables for power- and thrust coefficients are calculated. The pitch and generator torque actuators are modelled by respectively 2nd and 1st order linear systems with explicit constraints on the states.

The governing equations of the floating wind turbine are linearized for later use by the controller algorithm giving a time-discrete linear state space description of the wind turbine

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k \tag{1}$$

$\mathbf{A}$ and $\mathbf{B}$ are the system and input matrices respectively, $\mathbf{x}$ is the state vector, and $\mathbf{u}$ is input vector and k is the time index.

3 MODEL PREDICTIVE CONTROL

3.1 Disturbance and State Estimator

A disturbance model is designed to model the mismatch between the linearized control design model and the nonlinear simulation model. The disturbances and states are estimated with a predictive Kalman filter setup. The origin of the linearized variables of the linearized control design model is shifted to achieve offset-free control. The origin shifting is dependent on the estimated disturbances and changes in reference trajectory.

3.2 Constrained Linear Quadratic Regulator

The constrained LQR problem for the origin shifted case can be written as

$$\min_{x,u,\varepsilon}\left\{\frac{1}{2}\mathbf{x}_N^T\overline{\mathbf{Q}}\mathbf{x}_N + \sum_{k=0}^{N-1}\frac{1}{2}(\mathbf{x}_k^T\mathbf{Q}\mathbf{x}_k + \mathbf{u}_k^T\mathbf{R}\mathbf{u}_k + 2\mathbf{x}_k^T\mathbf{M}\mathbf{u}_k) + \sum_{k=1}^{N}\frac{1}{2}(\boldsymbol{\varepsilon}_k^T\mathbf{Z}\boldsymbol{\varepsilon}_k + \mathbf{z}^T\mathbf{u}_k)\right\} \tag{2}$$

Subject to the following constraints

$$
\begin{aligned}
&\mathbf{x}_0 = \hat{\mathbf{x}}_j \\
&\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k, && k = 0,1,\dots,N-1, \\
&\mathbf{D}\mathbf{u}_k - \mathbf{G}\mathbf{x}_k \le \mathbf{d}, && k = 0,1,\dots,N-1, \\
&\mathbf{H}\mathbf{x}_k - \boldsymbol{\varepsilon}_k \le \mathbf{h}, && k = 1,2,\dots,N, \\
&\boldsymbol{\varepsilon}_k \ge \mathbf{0}, && k = 1,2,\dots,N
\end{aligned}
\tag{3}
$$

Where $\hat{\mathbf{x}}$ is the estimate of the current state at global time index j and $\boldsymbol{\varepsilon}$ is a slack variable to enable soft constraints. The optimal constrained control sequence is calculated and the first instance of the sequence is actuated.

4 SIMULATIONS

Simulations are carried out the aero-servo-elastic code HAWC2 developed by Risø DTU. A multi-body nonlinear model of the floating wind turbine is controlled by the MPC algorithm, which is based on the simple control design model of the floating wind turbine.

5 CONCLUSIONS

In this paper the model predictive control is presented. A model describing the key elements of wind turbine dynamics have been presented, thus enabling model-based control methods. It has been shown that controller setup handles changing wind speeds and operating conditions. Simulations show that model predictive control ensures that no hard constraints are violated and that soft constraints are attempted to be honored when possible. The successful control of a simulated floating wind turbine has been demonstrated. Control of electrical power output has been the primary concern in this paper but other variables such as generator speed could be given higher priority at the expense of power output variability.

BIBLIOGRAPHY

[1] "Technical Note - Press Release," Tech. rep., Blue H, December 2007.

[2] "Pioneering wind turbines for deep water locations," Tech. rep., SWAY.

[3] Nielsen, F. G., Hanson, T. D., and Skaare, B., "Integrated Dynamic Analysis of Floating Wind Turbines," Proceedings of OMAE2006, 2006.

[4] Trainelli, L., Sirchi, W., Savini, B., Croce, A., and Bottasso, C. L., "Aero-servo-elastic modeling and control of wind turbines using finite-element multibody procedures," Multibody System Dynamics, Vol. 16, No. 3, 2006, pp. 291–308.

[5] Henriksen, L. C., "Model Predictive Control of a Wind Turbine with Constraints," EWEC2008 Online Conference Proceedings, 2008.

[6] http://www.statoilhydro.com/en/TechnologyInnovation/NewEnergyAndRenewables/Wind/VindTilHavs/Pages/Hywind.aspx.

Characterisation of Wind Variability over the North Sea

Claire Vincent[1]

[1)] Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Denmark.

ABSTRACT

A non-stationary spectral technique is used to deduce time evolving amplitudes and frequencies in a 3 month time series of 10 minute wind observations, measured at a 62 metre meteorological mast in the Danish North Sea in Autumn 2002. It is illustrated that there is a strong preference for the most intense variability episodes to occur in onshore flow, and that most of these events are associated with precipitation.

KEYWORDS

Non-stationarity, Wind variability, Predictability

1 INTRODUCTION

Forecasting intense episodes of wind variability is an important issue for grid integration of large offshore wind farms [2]. With a view to understanding the physical processes driving episodes of intense wind fluctuations, this work develops methodology for characterising the favourable atmospheric conditions for these events. An index of wind variability is developed and used to identify variability episodes from cup anemometer measurements taken at a 62 m measurement tower in the Danish North Sea near the Horns Rev wind farm in 2002. In section 2, the index of wind variability is described. In section 3, results are presented, with a particular focus on the period September to November 2002. Concluding remarks are given in section 4.

2 ANALYSIS METHODOLOGY

2.1 Non-Stationary Variance in Wind Observations

It is difficult to define a time scale over which it is possible to classify a time series of wind observations as statistically stationary. Statistical properties of the wind are modulated on a synoptic scale by the passage of large scale weather systems, but also on meso- and micro-scales by phenomena such as passing showers and clouds [1], intermittent bursts of turbulence [4] and changes in surface stability. This presents challenges for spectral analysis of variance, since a Fourier decomposition makes use of the assumption that the statistical properties of the time series are constant in time.

claire.louise.vincent@risoe.dk

2.2 Methodology

In this study, an adaptive spectral method known as the Hilbert-Huang transform [3] is used to uncover the time evolving amplitudes and frequencies that constitute the total wind signal. The Hilbert spectrum, which is a map of amplitude as a two-dimensional function of time and frequency, can be binned according to wind direction to create a heat map of average variability as a function of frequency and direction. The Hilbert spectrum may also be integrated over a frequency range of interest to create a scalar time series of total wind variability. These methods are applied for the period September to November 2002, months during which the most intense variability events are found.

3 RESULTS

3.1 Variability as a function of Wind Direction

Figure 1 (left) shows a heat map of amplitude of fluctuations as a function of wind direction and frequency, averaged over the three month period September to November 2002. The darker colours show regions of highest average variability. The plot shows that there is a strong preference for the wind directions 200 to 360 degrees (corresponding to onshore flow coming from the North Sea) for the most intense variability events. The plot on the right shows a stacked bar plot of precipitation events over the same time interval, where a ‘precipitation event’ is a record of greater than 0.2mm in any three hour period. It is seen that the most favourable directions for precipitation are also in the range 200 to 360 degrees, suggesting that there may be a link between precipitation and intense wind variability.

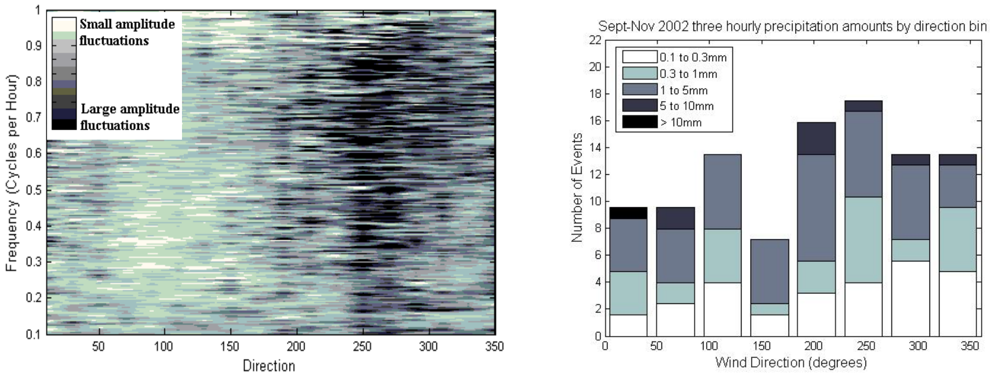


Figure 1: Left: Map of Variability as a function of frequency and wind direction: Sept - Nov 2002. Right: Stacked histogram of precipitation events by wind direction: Sept – Nov 2002.

3.2 Case Study: Intense Autumnal Variability Episodes

The connection between Autumnal variability episodes and precipitation was explored using heatmaps similar to that in Fig. 1, but with precipitation on the horizontal axis. Although not shown here, it was found that autumnal variability events are strongly associated with precipitation in onshore flow, while precipitating offshore flow is less likely to lead to intense fluctuations. As an example, a 5 day time series of wind speed (days 295 to 300, 2002) is shown in Fig 2. The plot shows that each precipitation event is associated with a peak in the wind variability (indicated by the dotted lines, which connect peaks in the variability metric with precipitation events). Further, the flow is mostly in the range 200 to 360 degrees.

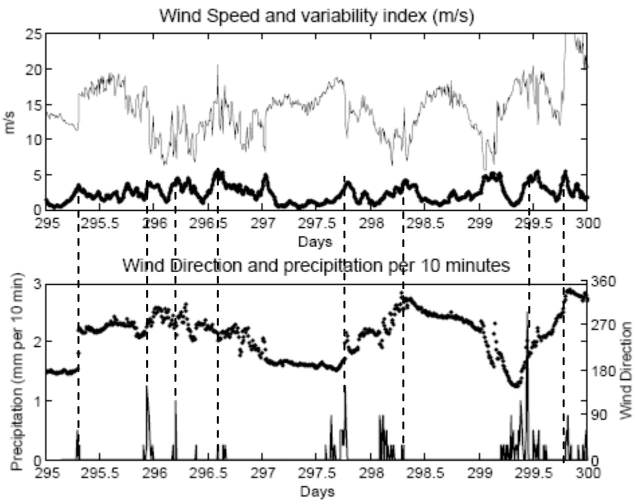


Figure 2. Time series from days 295 to 300 in 2002. Upper: Thin - Wind speed at 62m, Thick - Variability index. Lower: Dotted - Wind Direction, Thin – Precipitation per 10 minutes.

4 CONCLUSIONS

This paper describes a method for characterising non-stationary spectral information in a time series of wind speed observations from a 62 m tower in the North Sea. The method was applied to data from the period September to November 2002, and it was shown that there is a strong preference for onshore wind directions for the most intense variability events during these months. Further, variability events occurring in onshore flow (coming from the North Sea) were nearly all linked with precipitation.

BIBLIOGRAPHY

[1] Andreas, E.; et al.: Identifying nonstationarity in turbulence series. Bound. Layer Meteor., Vol 127, 37-56, 2008.

[2] Giebel, G.; et al: The state-of-the-art in short term prediction of wind power – a literature overview. Deliv. rep d1.1, Project ANEMOS, 36 pp 2003 [Available from http://anemos.cma.fr/].

[3] Huang, N.; and Z. Shen: The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. Proc. Roy. Soc. A, Vol 454, 903-995, 1998.

[4] Stull, R; An Introduction to Boundary Layer Meteorology, Kluwer Academic Publishers, Dordrecht, 1988, p 395.

ACKNOWLEDGEMENTS

I would like to acknowledge my PhD supervisors, Gregor Giebel and Pierre Pinson for their assistance and support in completing this work. Measurement data was supplied by Vattenfall as part of the Danish Public Service Obligation (PSO) fund project ‘HRENSEMBLE – High Resolution ENSEMBLEs for Horns Rev’ (under contract PSO-6382), which is gratefully acknowledged.

How to consider turbulence effects for an appropriate definition of a wind turbine's power curve

Julia Gottschall and Joachim Peinke [1)]

[1)] ForWind / University of Oldenburg, Germany

ABSTRACT

In this contribution we discuss the impact of atmospheric turbulence on a wind turbine's power output and its modelling, repectively. Based on an analysis of the corresponding short-time dynamics we motivate the introduction of a so-called dynamical power characteristic. Assuming that the time series of the power output, conditioned on a fixed wind speed bin, is governed by a stochastic process, we reconstruct its deterministic drift dynamics, separated from the stochastic fluctuations. This characteristic gives the response behaviour of the turbine system and is independent of site-specific parameters as the turbulence intensity.

KEYWORDS

power performance, power curve, stochastic process, increment statistics

To characterize a time series of the atmospheric wind speed measured as the horizontal wind velocity component at one point in space (*u(t)*), we study the statistics of its increments $u_\tau(t) \equiv u(t+\tau)-u(t)$ where the time increment τ corresponds to the considered time scale. Typically the probability density function (pdf) of $u_\tau(t)$ shows an intermittent behaviour, i.e. the probability for large events is higher than it is expected on the basis of a normal distribution with the same standard deviation (see Fig.1 left and [1]). Analyzing the corresponding time series *P(t)* for the power output of a wind turbine that is exposed to the wind defined by *u(t)* and its increments $P_\tau(t) \equiv P(t+\tau)-P(t)$, we observe a similar intermittent behaviour but also a kind of relaxation (see Fig.1 right).

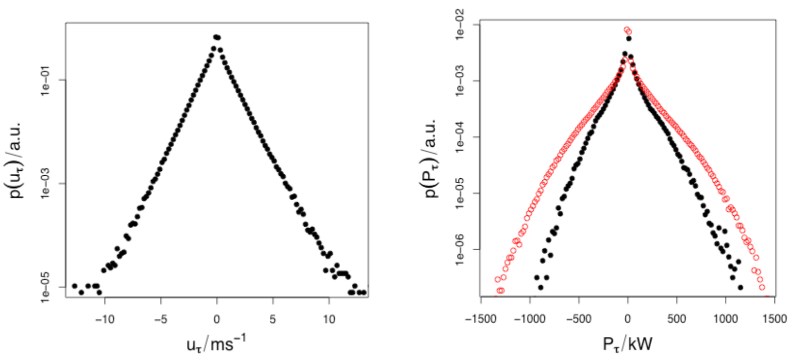


Figure 1:

Distribution of wind speed (left) and power output increments (right) for τ=20 s. Black dots for measured data. Red circles give reconstructed values, multiplying the time series *u(t)* with the derived power curve due to IEC [2] (cf. [3] for details).

julia.gottschall@forwind.de

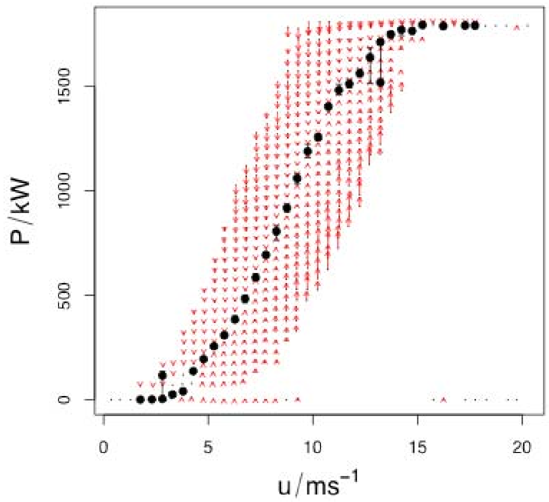
To translate this behaviour into a model for the effective power conversion dynamics given by *P(t)* we basically assume a deterministic system that is forced by a random function. The deterministic dynamics is given by a relaxation towards one or more stable fixed points for a fixed wind speed that give over the total range of wind speeds the power curve, and the stochastic force is related to the short-time fluctuations of *u(t)*. For each wind speed bin (here we adopt the binning proposed in [2]) we set up a (discretized) stochastic differential equation of the type

$$P(t+\tau)=P(t)-\tau\alpha(P(t)-P_{FP})+[\tau h(P(t))]^{1/2}\Gamma(t) \quad (1)$$

where α describes the relaxation as function of the deviation of the actual value *P(t)* from the fixed point P_{FP}, $\Gamma(t)$ is a noise process and *h(P(t))* fixes the amplitude of the respective stochastic fluctuations. If $\Gamma(t)$ corresponds to δ-correlated and Gaussian distributed white noise, Eq. (1) is a Langevin equation and one can apply well established reconstruction schemes to estimate the functions α and *h* directly from the data. But even when this requirement is not fulfilled, similar schmes can be used to estimate at least the values P_{FP} quite robustly (for details see [4]). What we obtain from this kind of analysis we call dynamical power characteristic, results for measured wind speed and power output data are shown in Fig.2.

Figure 2:

Dynamical power characteristic – red arrows represent reconstructed drift or realaxation coefficients for each wind speed bin, black dots denote estimated (stable) fixed points.



A crucial point to be discussed is the representativity of the highly sampled time series *u(t)* for the description of the power conversion process. On small time scales, e.g. delays between wind speed and power output measurements as well as shear effects with respect to the size of the rotor might be much more significant than for the averages used in [2].

BIBLIOGRAPHY

[1] Böttcher F, Barth St and Peinke J (2007) Stoch. Environ. Ris. Assess. **21** 299-308
[2] IEC 61400-12-1 International Standard
[3] Gottschall J and Peinke J (2007) J. Phys. : Conf. Ser. **75** 012045
[4] Gottschall J and Peinke J (2008) Environ. Res. Lett. **3** 015005

Wind tunnel measurements on an FX79W151A airfoil under unsteady conditions studying dynamic stall effects.

Gerrit Wolken-Möhlmann and Joachim Peinke

ForWind, University of Oldenburg, Germany

ABSTRACT

Forces acting on foils under unsteady conditions are an important issue for wind turbines. We present wind tunnel measurements using the integrated pressure over the wind tunnel walls. The results will be compared to pressure measurements on selected points on the upper side of the airfoil. These methods give new possibilities of studying the stall dynamics, like the determination of the separation point movement.

KEYWORDS

dynamic stall, unsteady aerodynamics, experiment.

1 INTRODUCTION

Good models for the characteristics of airfoils are essential for estimating the loads of wind turbine blades under unsteady inflow. Many of these models are derived from helicopter research and are modified for the boundary conditions of wind turbines, like a larger thickness of the foil. The sets of data for verification of these models are limited and in most cases restricted to sinusoidal changes in the angle of attack.

The goal of this research is dynamic stall measurements using the pressure distribution on the wind tunnel walls. This easily allows studying the characteristics of different foils. Furthermore, using a stepping-motor permits to control the angle of attack in different ways, e.g. stochastic or following a measured wind time series.

2 EXPERIMENTAL SETUP

For lift measurements, a closed test section is installed in the wind tunnel of the University of Oldenburg. Wind velocities of up to 50m/s can be obtained. Using a foil with a cord length of c=0.2, Reynolds numbers of up to $Re=7x10^5$ can be reached.

The foil is rotated via a stepping motor attached to the upper side of the test section, while the angle of attack is detected by an angular transmitter which is installed under the lower part of the test section (see figure 1). Angular velocities of more than 360°/s can be reached.

gerrit.wolken-moehlmann@forwind.de

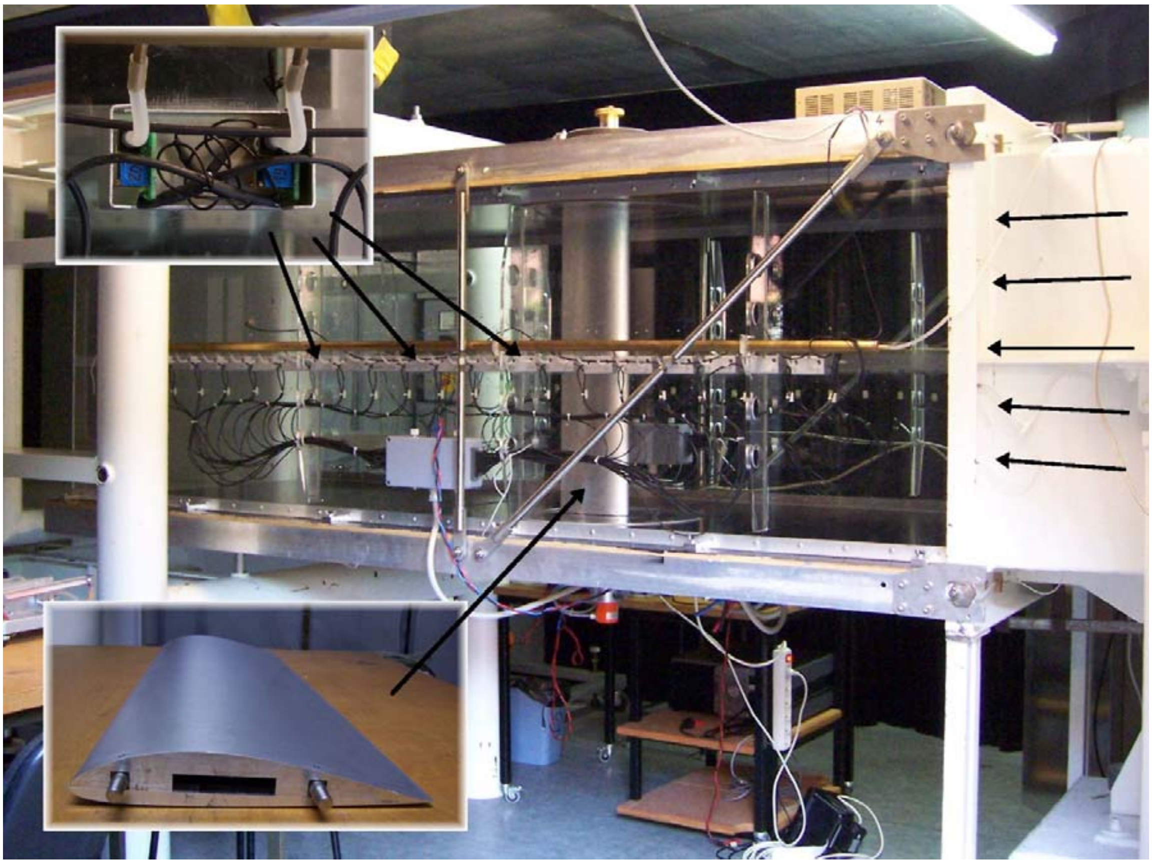


Figure 1: Picture of the closed test section with a close-up of the pressure sensor (top) and the FX79W151A foil (bottom).

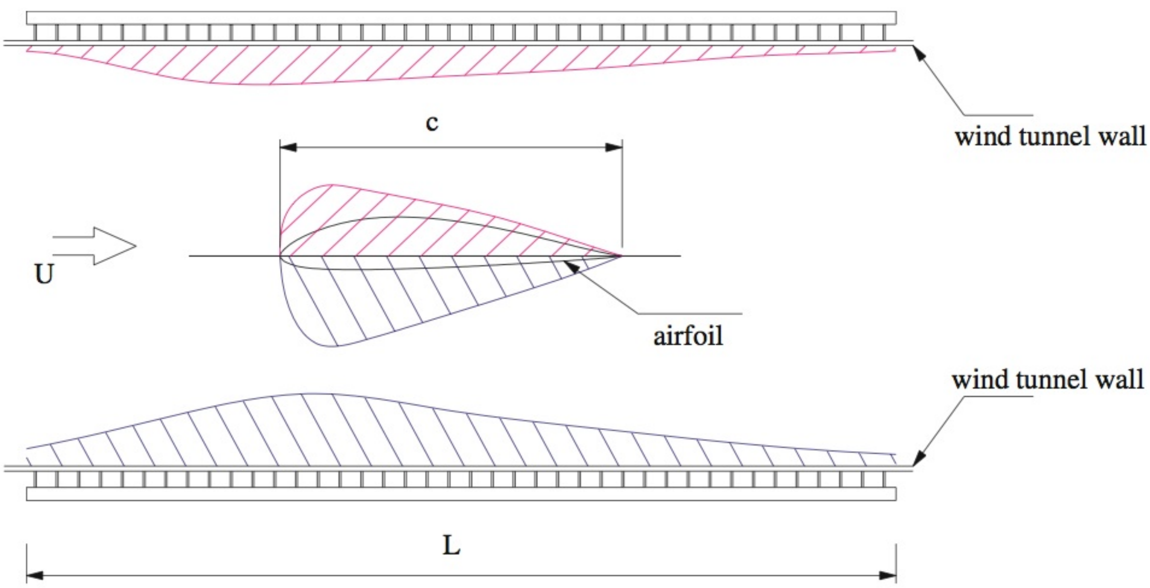


Figure 1: Sketch of the foil in the test section (top view) with the pressure distribution over the foil and the wind tunnel walls.

The lift is observed via the pressure distribution over the wind tunnel walls [1,2]. For this purpose every wall of the test section is equipped with 40 pressure sensors over a distance of two meters. The eighty signals are acquired by an A/D converter and analysed by software that also accounts for the time delay of the pressure field.

3 RESULTS

Static lift curves were measured and compared to literature values (see figure 3).
Under dynamic pitching of the angle of attack, typical dynamic stall behaviour with an overshooting in lift during the period of increasing angle of attack followed by a rapid decrease can be observed (see figure 4). There could be additional peaks in lift caused by vortex shedding. During the period of decreasing angle of attack, the lift matches again the static lift curve, creating a hysteresis loop.
Experiments were accomplished for sinusoidal pitching of the foil, defined by different mean angles of attack, oscillation amplitudes and frequencies.
The experiments point to an increase of the maximum lift under increasing angular velocities. Lift values of about 80% over the maximum static lift were observed.

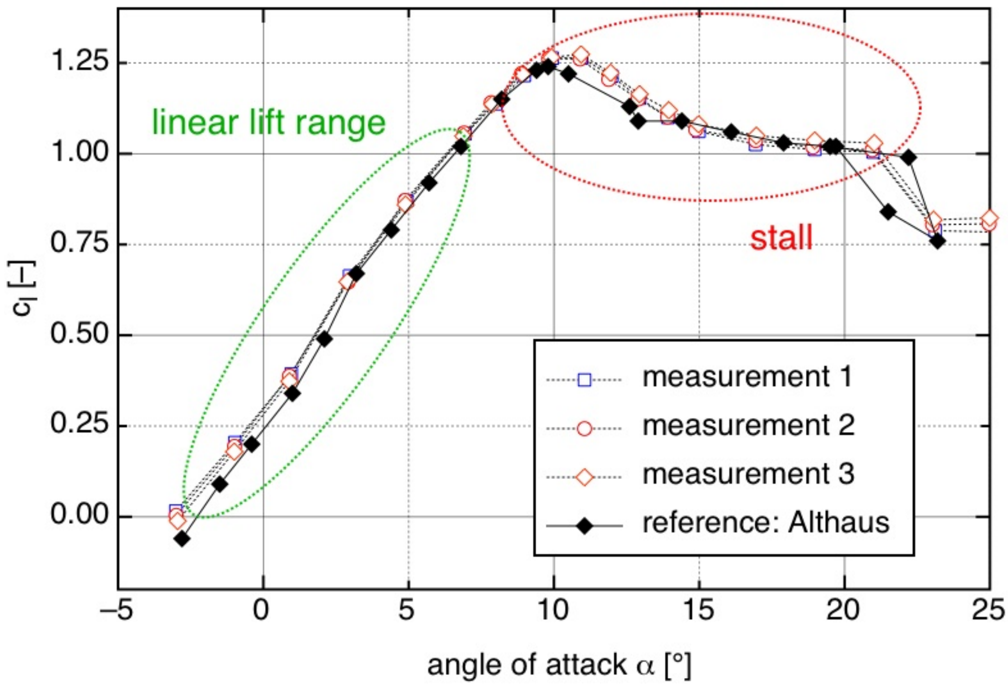


Figure 2: Comparison of measurements and literature values from [3].

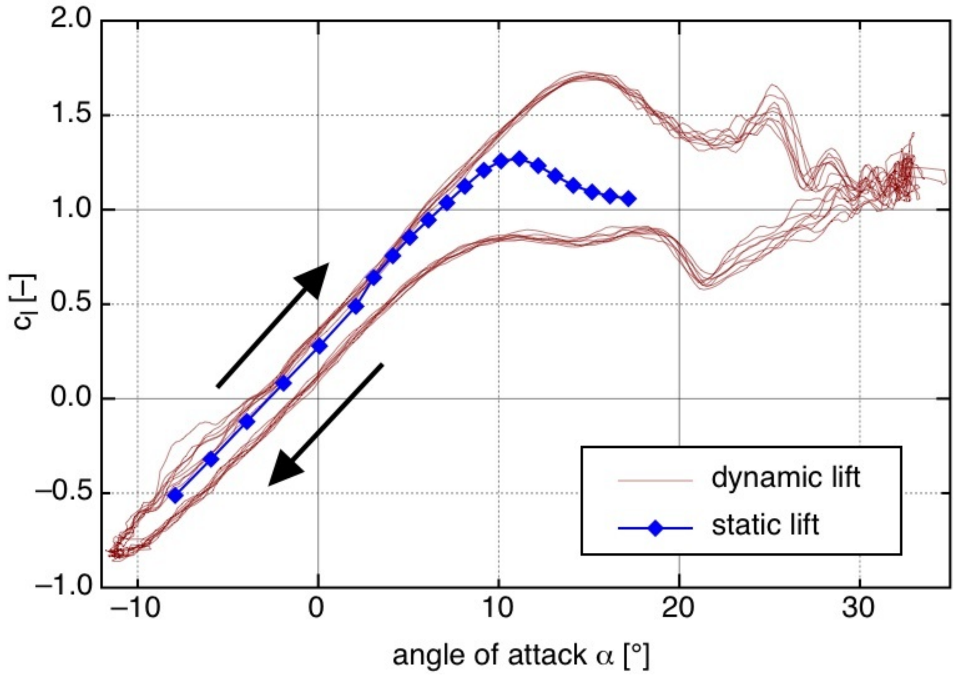


Figure 3: Measurements under unsteady conditions show typical dynamic stall behaviour.

4 CONCLUSIONS

Static lift curves could be reproduced using the described set-up. Lift curves observed under fast changing angles of attack show the characteristic dynamic stall behaviour, like the overshooting and further peaks in the lift just as a distinct hysteresis. Nevertheless it has to be checked if vortex shedding or wind tunnel blockage at higher angles of attack interfere with this method of measurement.

BIBLIOGRAPHY

[1] Althaus, D.: Measurement of lift and drag in the laminar wind tunnel

[2] Althaus, D.: Tunnel–wall corrections at the laminar wind tunnel

[3] Althaus, D. and Wortmann, F.X. : Stuttgarter Profilkatalog I, Vieweg Verlag, 1981

A Panel Method – Free Wake Code for Rotor Aeromechanic Analysis

Miquel Roura[1], Alvaro Cuerva[2]

[1,2] Universidad Politécnica de Madrid, Spain

ABSTRACT

Under the hypothesis of high Reynolds number flow, incompressible fluid and non-stalled flow conditions, Panel Methods turn out to be an efficient model for calculating rotor aerodynamics. In this paper a Panel Method combined with a Free Wake methodology is presented. The main code characteristics are: i) the rotor three-dimensional geometry is modelled, ii) the flap degree of freedom is considered, iii) the rotor wake is divided into near wake and far wake with only the tip vortex, iv) near wake and far wake are allowed to evolve with the local velocity, v) flow periodicity condition is assumed. Finally two code validations against experimental data are presented: i) NREL Phase IV in field yawed wind turbine (Schepers, 1997) and ii) Harris' aeromechanic experiment (Harris, 1972).

KEYWORDS

Panel method, free wake, aeromechanic

1 INTRODUCTION

During the last 30-40 years, systems which incorporate rotatory wings, like helicopters and wind turbines, have been playing an important role in the civil and military transport and in the production of electrical energy respectively. Helicopters, for their hovering flight capabilities, vertical taking off and landing, are used in multiple applications. Consider, for example, aerial vigilance, air ambulance, actuations in difficult to access places, etc. Likewise, wind turbines, due to the big amount of electrical energy demand, constitute one of the renewable energies with greater penetration. As an example, 34 GW were installed in Europe in 2005; in 2020 around 180 GW are projected to be installed (EWEA 2005). However, both sectors are not exempt of technical problems that require basic knowledge development, as European Union has recently identified (EWEA 2005) for the wind turbine rotor aerodynamics case.

Blade Element Theory (BET) is the industrial most widely used methodology for calculating rotor performances. Its simple formulation, straightforward way of applying correction models (non-stationary, compressibility, dynamic stall, etc.) and its fast runtime make it suitable for industrial applications. Panel Methods are the next step in complexity.

miguel.roura@upm.es

As stated above, they can solve the flow around three-dimensional rotor geometry in unsteady motion. Their main problem, in comparison with BET models, is the higher difficulty to introduce models that allow Panel Methods to consider viscosity and dynamic stall. Additionally, Panel Methods have to be combined with a wake model that provides the wake geometry: generally for the rotor case, due to its non-stationary nature, a Free Wake model is used. Solving the Free Wake equations is one of the most time-consuming processes. For this reason the wake is divided into two parts, a near wake, where a general vorticity surface is considered, and a far wake with only the tip vortex. Finally, it is remarked, that the problem is solved by a relaxation or iterative approach which imposes rotor periodic working conditions. Periodic working conditions are not very restrictive for a wind turbine or helicopter and many practical situations, such as axial and yawed conditions, can be analyzed.

2 EXPERIMENTAL CODE VALIDATION

Here we present two comparisons of the Panel Method – Free Wake code against experimental data: the first validation is performed against NREL Phase IV yawed wind turbine experiment (Schepers, 1997); the second validation is carried out against Harris' aeromechanic experiment (Harris, 1972).

2.1 Unsteady Aerodynamics Experiment (1987-2000)

The main objective of the Unsteady Aerodynamics Experiment (UAE) is to provide information to characterize wind turbine three-dimensional behaviour. The UAE experiment has been performed in six different campaigns. Here NREL Phase IV in field data is used to compare: before comparison, data should be analyzed to find out a period of time where the wind turbine is working in periodic conditions. The following working conditions are encountered: 21° yawed wind turbine with incident velocity $U_{\infty} = 9.78 m/s$ and tip pitch angle $\theta_{tip} = -2.9^{\circ}$. The comparison of the tangential and normal force coefficients is depicted in the figure below.

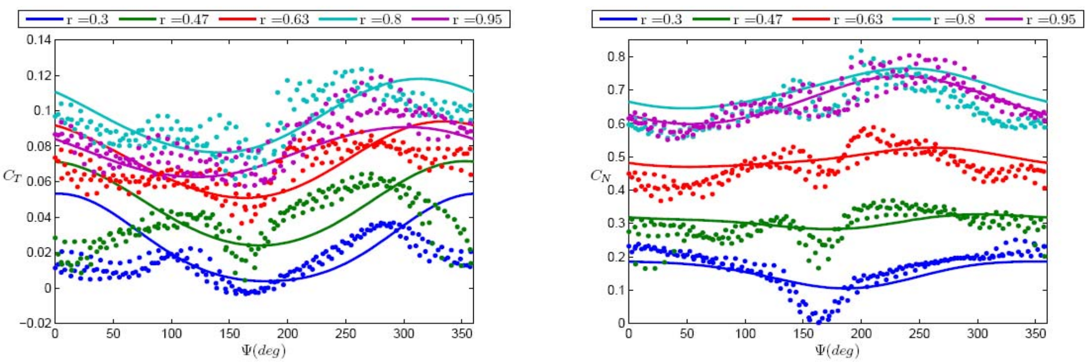


Fig.1 Azimuthal variation of the tangential and normal force coefficients at different blade sections (points experimental, solid line numerical).

2.2 Harris' experiment (1972)

The experiment conducted by Harris in 1972 is used to validate the rotor trimming methodology for a case of articulated blades. The experiment consists in measuring the blade flapping response of a four bladed articulated model rotor at different advancing velocities μ (equivalent to yawed wind turbine conditions): given the values of the cyclic pitch angles $\theta_c = 0.73^o$ and $\theta_s = 0^o$, the rotor collective pitch angle θ_0 and the shaft angle α_s are adapted to obtain the desired values of the blade loading coefficient C_T / σ and tip path plane angle of attack α_{TPP}. Finally, the blade flapping coefficients $(\beta_0, \beta_c, \beta_s)$ are measured.

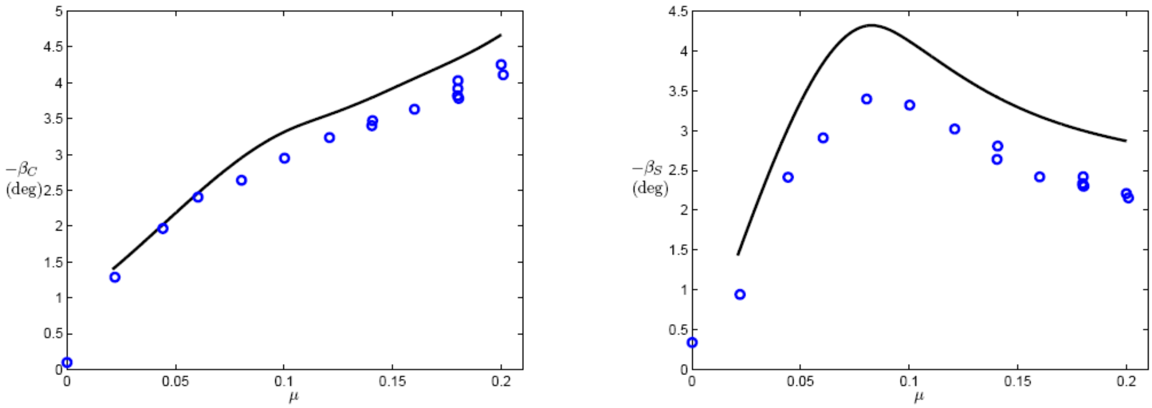


Fig.2 Blade flapping coefficients at different advancing velocities (circles experimental, solid line numerical)

3 CONCLUSIONS

A Panel Method - Free Wake methodology has been presented and validated against two experiments, showing the code capabilities to predict yawed wind turbine aerodynamics and articulated rotor flapping response. At present, new simulations of a teetering rotor in yawed conditions are being performed.

BIBLIOGRAPHY

[1] EWEA. 2005. Prioritising Wind Energy Research: Strategic Research Agenda of the Wind Energy Sector.

[2] Schepers, J.G., et al. 1997. "*Final report of IEA Annex XIV: Field Rotor Aerodynamics.*" *ECN-C-97-027*.

[3] Harris, F.D. 1972. "Articulated Rotor Blade Flapping Motion at Low Advance Ratio." *J. American Helicopter Soc*. 17 (1).

Stability curves for wind turbine blades

Gabriel G Martinez H[1)]

1. Technical University of Denmark, Denmark

ABSTRACT

A linear approach is used to construct the stability curves for a rotating wind turbine blade for transition prediction. A database that contains the tangential and radial velocity components for different operational conditions designated by the Rossby number (Ro) at different sections on the blade (c/r) is used as an input for the stability analysis. The present work focus on the solution of the stability equations at the attachment line and on the Blasius flow in a rotating reference frame.

KEYWORDS

Transition, Stability curves, Database

1 INTRODUCTION

Laminar-turbulent transition is a complex process in which the most stable condition is reached when the flow transitions into turbulent by the action of external disturbances. If the boundary layer is seen as an open system, the response to external disturbances is investigated on this work. To represent disturbances or waves, two wave vectors are needed, one on the tangential direction represented by α and other the radial direction β, and the radian frequency by ω. If the approach is spatial the wave vectors are complex and the radian frequency real, while, if the problem is temporal the wave vectors are real and the radian frequency complex. The stability analysis is reduced to the following eigenvalue problem:

$$f\,(\alpha_r,\alpha_i,\beta_r,\beta_i,\omega_r,R) = 0 \quad (1)$$

$$f\,(\alpha_r,\beta_r,\omega_r,\omega_i,R) = 0 \quad (2)$$

Different strategies can be used, all of them depend on the parameters that are keep fixed when solving equation 1 or 2 or the relation that is obtained between them. The propagation direction, magnitude and growth rate of disturbances play a important role in the transition prediction, one of the complications in the solution is that disturbances not necessary follow the stream line direction, one technique is to maximize the grow rate on the free parameter, a complete review is giving by [1]. The actual method makes use of the envelope method that solve together for the TS and CF instability mechanisms. In this

gstgab@mek.dtu.dk

approach $\alpha_i = 0$, $\beta_i = 0$ and $(d\alpha/d\beta)$ a real number. On the relevant literature relatively high number of the actual research on stability in 3D flows has been directed to swept wing on airplane airfoils, but they do not include rotational effects in the stability equations. The actual method is valid if level of turbulence is below 1%.

2 APPROACH

To obtain the initial solution that governs the full stability of blade and the general behaviour of the rotational effects, two cases are considered: the attachment line and the Blasius profile on the rotating blade, the first case do not depend on a particular type of airfoil, however depends on the Rossby number (Ro) and the local solidity (c/r). Have been observed both numerical and experimental that the shape of the neutral curves when the rotational effects are included is that the critical Reynolds and the neutral curve are displaced to a higher value [2].

2.1 Results

The numerical results [3] have been reproduced for the 2D solution for the dimensionless pressure gradients m=0 and m=1 on fig 1. The range for parameters tested was Ro [0.5-0.90] and c/r [0.010-0.35] for the 3D case. The effect of the increasing the Rossby number is

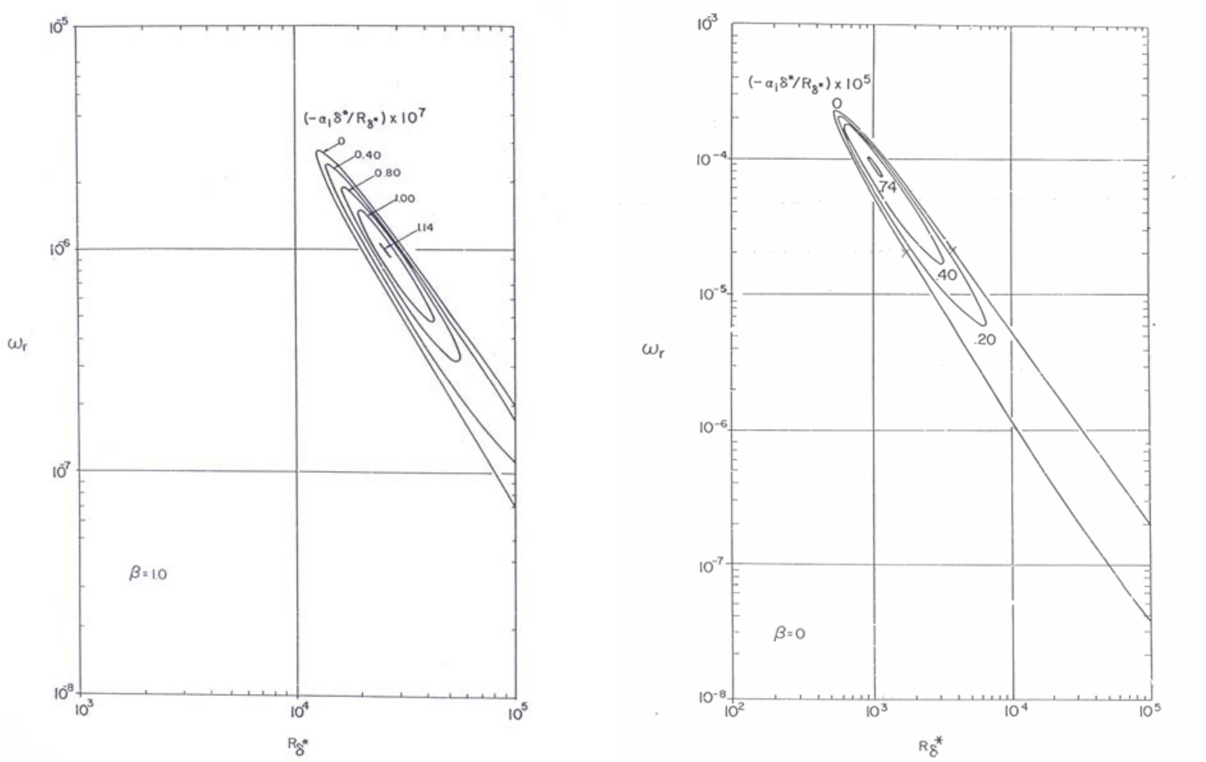


Figure 1: Spatial stability curve, left figure m=1, right figure m=0.

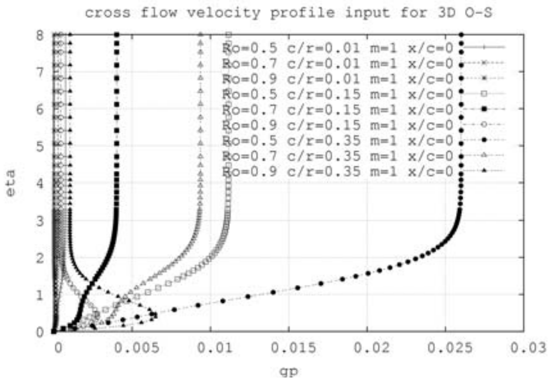


Fig 2 Cross flow velocity profile m=1

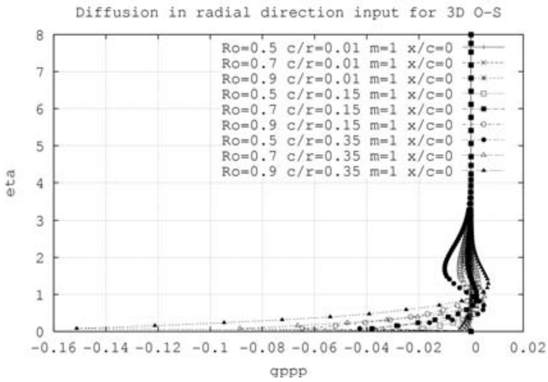


Fig 3 Diffusion in the Bondary-layer m=1

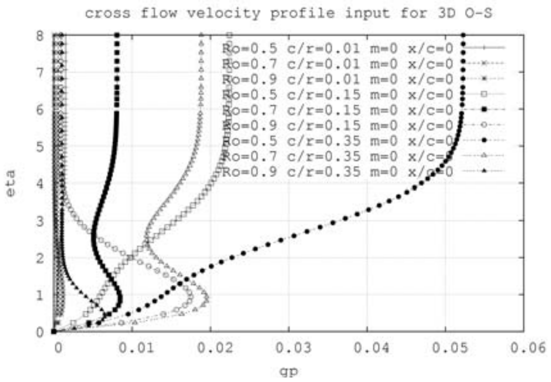


Fig 4 Cross flow velocity profile m=0

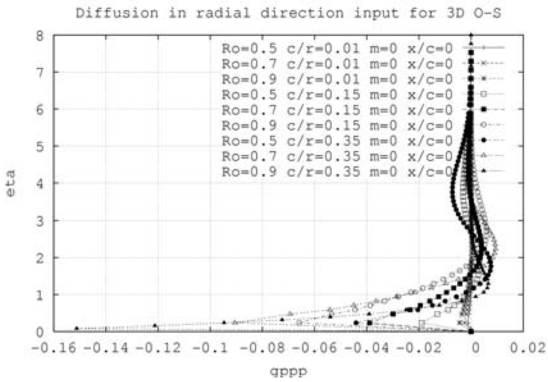


Fig 5 Diffusion in the Boundary-layer m=0

that the Coriolis force increase the inflection point, therefore the cross velocity profile is unstable at leading edge and the Rcr of the tip is decreased , the tangential flow at leading edge is stable.

3 CONCLUSIONS

The present study cases gave very valuable information for the construction of the stability curves and the effect of the rotational effects on the stability properties of the cross flow velocity profiles.

BIBLIOGRAPHY

[1] Arnal D. Practical transition predictions methods: subsonic and transonic flows. Advances in Laminar-Turbulent transition modeling. RTO-AVT-VKI Lecture Series 2008

[2] R.J.LINGWOOD 1995, Absolute instability of the boundary layer on a rotating disk. J. Fluid Mech. 299, 17-33

[3] A.R. Wazzan, T.T. Okamura and A.M.O. Smith Spatial and temporal stability charts for the Falkner-Skan boundary-layer profiles RepNo. DAC-67086. McDonnell Douglas

New Construction Opportunities for Grouted Joints of Offshore Wind Turbine Structures

Peter Schaumann[1], Stephan Lochte-Holtgreven[1]

[1] ForWind - Center for Wind Energy Research

Institute for Steel Construction, Leibniz Universität Hannover, Germany

ABSTRACT

Grouted joint connections are well known from the offshore oil and gas Industries. In the last decade grouted joints were also used in OWT- Structures for the connections between pile and tower section of monopile support structures. Valid recommendations do not contain any useable design approximations for this type of connection. Latest investigations show that the grouted connection can also be used for hybrid towers of Onshore Wind Turbines and as a connection between offshore gravity basements and tower. Within this abstract new construction opportunities for grouted joints in OWT will be presented.

KEYWORDS

Support Structures, Fatigue, Grouted Connections, Hybrid Structures, Offshore

1 INTRODUCTION

The German Wind industry goes offshore. In comparison to the existing European Offshore Wind Farms the German Wind Farms are suited in regions with water depths of about 40 to 50 m. The optimised support structures for these water depths are jacket or tripod structures. For near shore Wind Farms suited in water depths of about 25 m maximum the monopile support structure is the best solution.

2 STATE OF THE ART

The connection between the monopile foundation and the tower of Offshore Wind Turbine structures (OWTs) can be realised by pile-to-pile-connections, the so called grouted joints (see Figure 1). The gap between the monopile and the transition piece is filled with a high performance grout material. This from the oil and gas industry well known connection makes it possible to compensate inclinations due to the installation process. In comparison to the offshore gas industry the predominating load of Offshore Wind Turbines structures is a bending moment due to wind and wave action. Valid standards ([1]-[3]) give design rules for axial loaded grouted connections.

lochte@stahl.uni-hannover.de

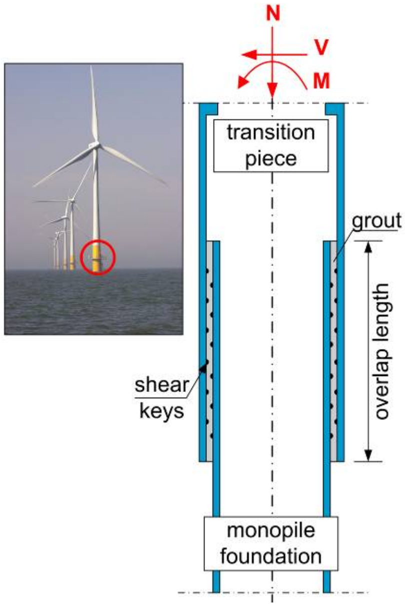


Figure 1: Grouted connection for a monopile support structure

But for grouted joints under predominating bending moment there are only a few design recommendations. The Germanischer Lloyd [2] and the DNV [3] recommend for the overlap length of the connection under predominating moment the following overlap factor:

$$f_{OL} = L_g / D_P = 1.5 \quad (1)$$

with the effective grout length L_g and the diameter of the monopile D_p. Normally, steel pipes with plain surfaces are used. To increase the normal and shear strength stiffness of the connection the valid standards allow the application of shear keys. Besides the Eq. 1 there are no additional design guidelines. The influence of the shear keys is not finally clarified as well. The engineer has no guideline for an economic and save design of the structure. Grouted connections were used for monopile support structures of OWTs so far, but can also be used for gravity basements (see Figure 2 (left)) and hybrid towers of Onshore Wind Turbine structures (see Figure 2 (right)). Design guidelines for these hybrid connections do not exist.

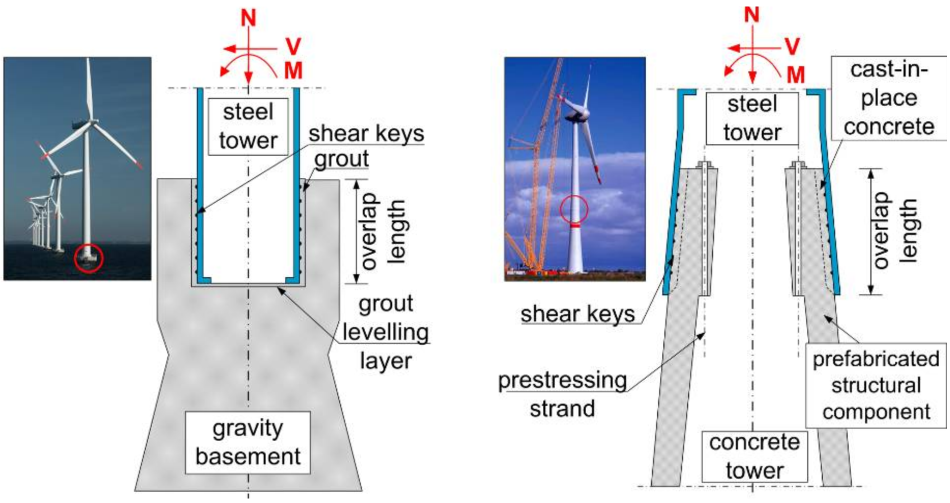


Figure 2: Grouted connection for gravity basements (left) and for onshore hybrid towers (right)

3 CONSTRUCTION OPPORTUNITIES

Gravity basements are used for OWTs in low water depth. The Offshore Wind Farm Middelgrunden (S) and Nysted (Dk) are supported by heavy concrete foundations. The transition piece between concrete foundation and steel tower was encased in concrete. For the installation of the turbine it was necessary to adjust the basements absolutely planar. Inclinations due to imperfections of the foundation were not acceptable. By using a grouted connection which is installed subsequently it is possible to build a typical sleeve foundation. The installation of the basement is independent from the installation of the tower. Inclinations due to the installation process or settlements of the ground can be compensated by the grouted connection. This construction opportunity can also be used for onshore hybrid towers. The wind conditions mainly depend on the height of the turbine. Steel towers with diameters of about 4 m cannot be used for tower heights between 100 and 140 m. For these tower heights it is recommendable to use hybrid tower constructions. The lower part of the tower is build with precast concrete components, the upper part with steel tubes. The connection between concrete and steel tower is normally build by bolted or prestressed connections. The advantage of grouted connections is that they are nearly maintenance free in comparison to bolted or prestressed connections.

4 INFLUENCE OF SHEAR KEYS

Valid standards and regulations allow the application of shear keys to increase the stiffness of the connection. It is recommendable to apply shear keys in the center of the connection ([4] - [5]). Shear keys at the ends of the transition lead to increased stresses.

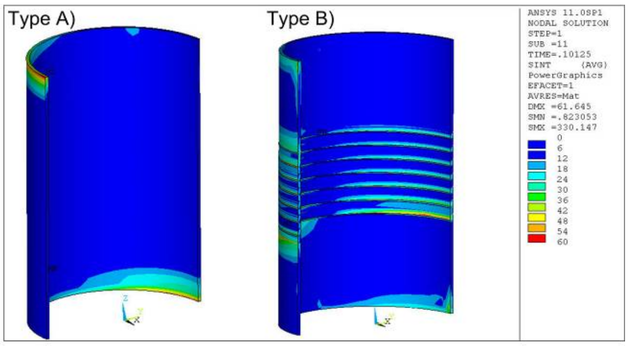


Figure 3: Grouted Connection without (left) and with shear keys (right)

Figure 3 shows the stress intensity of grouted connections without (Type A) and with shear keys (Type B). It can be seen that the stresses at the ends are decreased significantly. A centred application of shear keys leads to an uniform stress distribution. That is why connections with shear keys show a better fatigue behaviour.

5 CONCLUSIONS

Grouted connections can also be used in gravity basements of OWT or for connections of hybrid tower sections to compensate inclinations due to the installation process. In comparison to bolted or welded connections grouted joints are nearly maintenance free. The stiffness of grouted connections could be increased by the application of shear keys. Material and installation time will be reduced.

BIBLIOGRAPHY

[1] Bundesamt für Seeschifffahrt und Hydrographie: Standard - Design of Offshore Wind Turbines Hamburg und Rostock, 2007

[2] GL: „Rules and Guidelines, IV Industrial Services, Part 2: Guideline for the Certification of Offshore Wind Turbines", Germanischer Lloyd Industrial Services, Hamburg, Edition 2004^

[3] DNV - Offshore Standard: DNV-OS-J101, Design of Offshore Wind Turbine Structures, Det Norske Veritas, Horvik, Norway, Draft 2004

[4] Schaumann, P.; Wilke, F.; Lochte-Holtgreven, S.: Nonlinear Structural Dynamics of Offshore Wind Energy Converts with Grouted Transition Piece, Proceedings of the European Wind Energy Conference EWEC 2008, Brussels, Belgium, 2008

[5] Schaumann, P.; Wilke, F.; Lochte-Holtgreven, S.: Grout-Strukturen für Offshore-Windenergieanlagen - Trag- und Ermüdungsverhalten, Stahlbau, Volume 77, Issue 09, Verlag Ernst & Sohn, Berlin, Germany, 2008

Exploiting Local Flow Structures for Building-Integrated Microgeneration

Nathan Hill

Durham University, UK

ABSTRACT

The wind environment of urban areas is characterised by flow separation and recirculation, which presents problems for microgeneration. However these flow structures also create large pressure differentials between building faces. Ducted turbines connecting high and low regions present an opportunity for microgeneration comparable to conventional micro-wind turbines.

Unsteady 3D Computational Fluid Dynamics models, backed up by some preliminary wind tunnel tests, are used to investigate the likely magnitude of this resource. The stability and size of the phenomenon is investigated with regard to the inherent variability of the oncoming wind speed and direction.

KEYWORDS

Wind resource, atmospheric flow, Micrositing, microgeneration

1 INTRODUCTION

Ducted turbines make use of the same flow separation that bedevils the placement of conventional small turbines [1]. They also have advantages in terms of safety and visual impact. They make use of pressure gradients that have previously been studied primarily from a structural perspective (that is, wind loading and estimating peak values to prevent damage). In this work an attempt is made to quantify the resource over long periods of time.

2 MATHEMATICAL FRAMEWORK

A mathematical framework was developed by Grant et al. At the University of Strathclyde [2]. They defined a pressure differential

$$\delta = (P_S - P_0)\Big/\left(\tfrac{1}{2}\cdot\rho\cdot V_0^2\right) \quad (1)$$

Where P_S is the stagnation pressure at the duct inlet and P_0 the static pressure at outlet. From these the optimum coefficient of performance (C_P) is found to be

$$C_P = \frac{2}{3\sqrt{3}} C_V \cdot \delta^{3/2} \quad (2)$$

Where C_V is the duct's velocity coefficient.

nathan.hill@durham.ac.uk

3 TYPICAL EXAMPLE

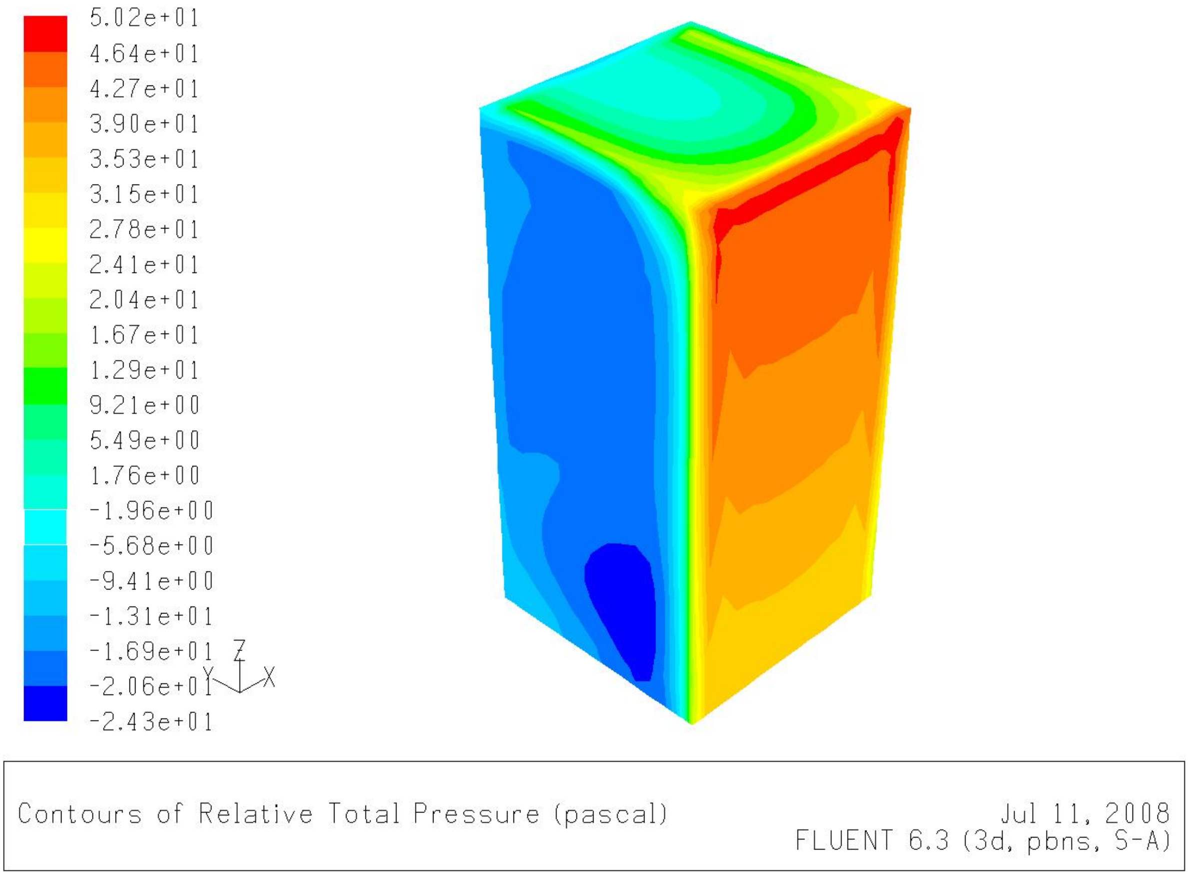


Figure 1 shows contours of total pressure on the walls of an isolated building in a steady wind with a logarithmic profile and a reference speed at roof level of 8.35 m/s. One possible configuration is an inlet in the centre of the facade at 95% height (close to the stagnation point) and an outlet in the centre of the roof. In this example, δ = 1.48, giving an optimum C_P of 0.695 (compare with the Betz limit, 0.592). This is, however, quite directional- similar ducts in the other three faces are essentially inactive in this case.

4 PLANNED INVESTIGATION

This example is a steady-state solution, and therefore ignores both the natural variability of atmospheric winds and the inherent time dependence caused by vortex shedding. The CFD model will be extended to give time-averaged estimates of the resource.

Air flow through ducts will tend to reduce the depth of pressure wells. Mass injection will be used to model this and estimate the extent to which the resource can be exploited.

BIBLIOGRAPHY

[1] Mertens, S. 'The energy yield of roof mounted wind turbines', Wind Engineering 27, no. 6 (2003) pp507-518

[2] Grant, A.; et al. 'Urban wind energy conversion: the potential of ducted turbines', Renewable Energy 33 (2008) pp1157-1163

SESSION 3-B
OPERATION, PLANNING AND ECONOMICS

(Parallel to the Session 3-A)

Thursday, 02.10.2008

09:30 – 11:40

Building 22A / Room 020

Supervisor:

Dr. S. Bart, ForWind

Chairman:

D. Cabezon, CENER

Design optimization of large scale horizontal axis wind turbines

Turaj Ashuri, Michiel Zaaijer

Delft University of Technology, DUWIND, the Netherlands

ABSTRACT

This paper describes the optimization process of a wind turbine. Cost of energy is the objective function. Design variables are structural parameters such as thickness. Design constraints are structural considerations such as fatigue and stresses. The entire wind turbine is modelled using FAST which is an aeroelastic simulator. Optimization process is carried out using an external optimizer which is linked with FAST. The aim of this work is to give a better insight in the economy and technical challenges of the future wind turbines in the range of 5 to 20 MW.

KEYWORDS

Design optimization, aeroelastic simulation, economy of larger wind turbines

1 INTRODUCTION

Design optimisation launches a search for better or more cost effective designs, which optimises an appropriate objective function and satisfies certain design constraints. Current wind turbines require structures that have suitable load carrying capacity and that are cost effective.

In this research, cost of energy is the objective function which can be optimized by maximising power production and minimizing structural weight. Design constraints are:

- The level of stresses in the structure for an extreme load case
- Fatigue by using Palmgren-Miner rule for 20 year lifetime of the turbine
- Eigen-frequencies of the blade and tower
- Tower and blade deflections

Design variables are blade, tower and high and low speed shaft structural properties.

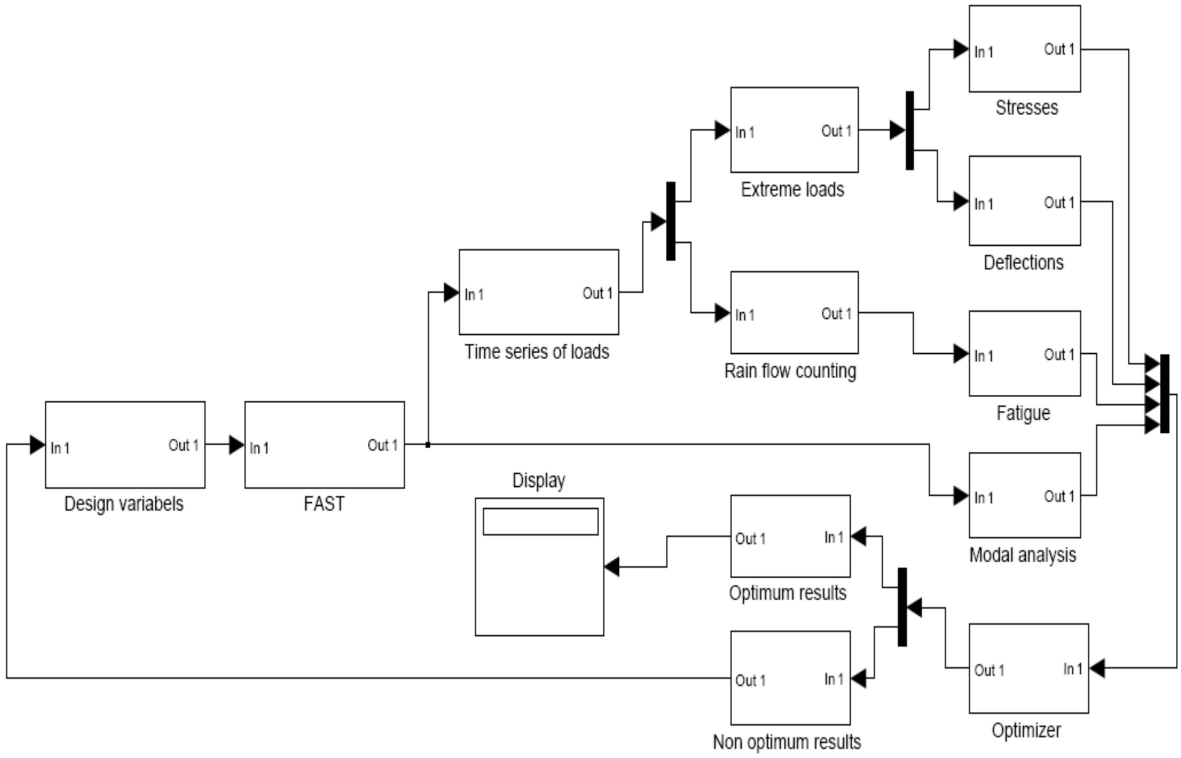
The wind turbine is modelled using FAST, which is an aeroelastic solver. For this purpose the 5MW NREL offshore wind turbine is used. It should be mentioned that this model acts as the function that is used to find the optimum. After finding the optimum of this configuration it

t.ashuri@tudelft.nl

will be up-scaled to 10, 15 and 20 MW and optimized, to see the economy and probable challenges of larger scales.

2 METHODOLOGY

In order to do an optimization process and find an optimum, the function under study (the aeroelastic model in FAST) should be evaluated several times by using new design variables. A loop for this repetitive job should be made which in this research is given in below figure:



3 RESULTS

Some results of this work are:

- Find out the critical issues relating to up scaling of wind turbines
- Propose solutions to avoid the critical issues
- Propose a suitable offshore wind turbine layout
- Guidance and recommendation for designing optimized components

4 ACKNOWLEDGMENT

The authors wish to acknowledge SenterNovem for their financial support of this research in the framework of the INNWIND project.

Decision making tool for trading wind energy in an electricity market

Petros P. Kritharas, Simon J. Watson

CREST (Centre for Renewable Energy Systems Technology), U.K.

ABSTRACT

Wind energy is making an ever-expanding contribution to the energy mix as well and its active trading within electricity markets becomes more important. However, due to the variable nature of wind, many techniques have been used to forecast generated power and minimise the uncertainty of this source of energy.

This paper will present a preliminary design of a decision making tool for trading wind energy. The decision making tool will use fuzzy classification and pattern recognition to reach an optimum strategic decision based on multiobjective methods and memberships taking into account the level of confidence versus the frequency of memberships.

KEYWORDS

Decision-making, forecasting, level of confidence, wind power plants, electricity markets

1 INTRODUCTION

Issues such as global warming as well as oil and gas price uncertainty due to political instabilities are among the highest priorities in the developed world as they create an energy market uncertainty. As a result, current policies globally encourage the use of renewable energy in an attempt to tackle the increase of carbon dioxide emissions and to diversify energy supply. In particular, the European Commission, by publishing the DIRECTIVE 2001/77/EC [4], set out the guidelines which all the Member States must comply with in order for each EU Member State to attain a 12% share of penetration from renewable energy sources by the year 2010. To meet this target, an increase will be required in the installed wind power capacity equal to 45-60 GW. Under a feasibility study which took place in 2002, the European Wind Energy Association (EWEA) concluded that wind energy is able to fully supply up to 12% of the world's demand for electricity even though if, according to the projections, the future demand will be double. In this hypothetical scenario, the EWEA extended even further its initial targets from 60 GW up to 75 GW of installed wind energy capacity by the year 2010 [19]. However, electricity networks were planned to support a certain number of power generation units. Given that, it is obvious that such energy penetration may raise technical and safety issues. Therefore, System Operator (SO) must ensure that supply will meet demand constantly whilst simultaneously managing a secure

kritharas@ieee.org

and safe system. The latter implies keeping both voltage and frequency within limits. The SO, in order to do so, controls them through spinning reserve, load following, load rejection reserves, and black starts. These support services are known as *ancillary services* and they are well documented as well as their influence in deregulated markets in [7, 14]. In summary, the SO is responsible for the accommodation of a variety of power generation plant (including that from renewable energy sources) in an electricity network to ensure the cost-effective balance of supply and demand taking into account transmission constraints. As a result of the technical issues mentioned, along with the liberalization of electricity supply industry, the SO has to find the optimum allocation of generation units to meet system demand. To make things more complicated, the economic and safe operation of a system depends also on the prevailing market mechanism. An overview of the electricity market structure in Europe as well as the bidding procedure and constraints can be found in [10]. In the UK, several changes have been made since 1989/90 when the UK Government introduced a centralized system known as the Electricity Pool. In 2001, the New Electricity Trading Arrangements (NETA) were introduced in England and Wales which were extended to Scotland in 2005 under the British Electricity Transmission and Trading Arrangements (BETTA). As a result, the wholesale market created for trading electricity within Great Britain initially caused a drop in prices due to competition though prices more recently (as of 2008) have increased due to fuel inflationary pressures. In one way, the new mechanism helps renewable generators as they have more freedom concerning with whom they trade their power through bilateral contracts.. However, generators are committed to adhere to their contracts. This means that they are obliged to compensate the SO for any imbalance caused by difference in contractual and actual outturn. Additionally, there is the perception that the power from wind farms is unreliable due to the stochastic nature of wind. Consequently, the economic dispatch of wind power presents a challenge.

The aim of this paper is to present a preliminary design of a decision making tool (DMT) for trading the electricity generated from wind farms into a competitive wholesale market. The proposed DMT is based on classifying weather data to determine the “future predictability” of wind speed, wind direction and thus site wind power. The classes determine the level of confidence in any future forecast. Forecasting can be made on any time scale from hours up to months ahead depending on trading requirements. These forecasts are assumed to be available as input to the DMT. Although short-term forecasting models are widely available, long term forecast models up to months ahead are less so. We propose a pattern recognition based analogue forecasting model which bases monthly forecasts on similar patterns in the past. When a new forecast becomes available, it is classified according to the classes determined above. Past trading decisions as well as past wind farm generation outturn data are also used as input to the DMT. Taking into account previous trading decisions as well as other factors such as maintenance of wind farms and penalty factors for generation imbalance, a new future trading decision is proposed. The purpose of the proposed DMT is to minimise exposure to market imbalance prices imbalance and to maximise profit by optimising the trade of the electricity generated from a portfolio of wind farms.

2 THEORY

2.1 Forecasting wind power

The value of wind power forecasting has a two-fold importance. Firstly, knowledge of the expected generation output from wind power plants provides confidence to the SO for when trying to achieve reliable and secure operation of network. Secondly, it enhances the value of wind generated electricity by giving vital information when participating in an energy market. This can be achieved both by providing higher value contracts due to better bidding strategies and by minimizing imbalance costs. Specifically, in a deregulated market, generators and suppliers (to whom the imbalance risk is often transferred) can avoid being penalised by choosing an optimum bidding strategy. However, this also depends on the market in question. As stated in [1] the rules can influence the selection of an appropriate bidding strategy. A study of the application of wind power forecasting and the associated economic benefits derived was presented in [17]. The author pointed out the significance of providing accurate forecasts 24 hours ahead and explained their contribution to the scheduled operation of conventional power plants. In another case study for England and Wales, it was shown that wind forecasts in combination with a statistical technique can lead to advanced and efficient maintenance planning and operation of conventional plant. Such productive operation of conventional plant can result in a fossil fuel saving of up to 25% [9]. During the last three decades, significant research has been carried out in the field of wind power forecasting with operational tools making their presence noticeable in the last 15 years. Findings vary depending on the selected approach (statistical or physical),the time horizon of the predictions or the area covered (single wind turbine/farm, sub-region, region or country). An up to date comparison and evaluation of the state-of-the-art of forecasting systems can be found in [11]. In addition, for a comprehensive overview of the prediction models, we refer to [3, 5, 8].

More recently, attention has been paid to developing operational tools to support decision-making for the optimum trade of electricity from wind farms. The two dominant methods for forecasting are point and probabilistic. The main difference lies in the fact that the probabilistic method includes the uncertainty associated with a forecast. In a study comparing the two methods, it was shown that probabilistic forecasts outperform point ones when used in combination with appropriate bidding strategies [13].

2.2 Decision making

The necessity for individual private producers (IPP) to minimise their risk and optimise their bidding strategies has resulted from a wide-spread international move from heavily regulated state monopolies in power supply to privatised de-regulated competitive wholesale markets for electricity, particularly in the developed world. Such markets give flexibility to IPPs to trade freely their electricity. However, as mentioned previously, there are several constraints limiting this freedom due to contractual agreements.. Therefore, generators and suppliers have to choose the best trading decision at any given time. Nevertheless, the best choice at the time does not always produce the best possible outcome. This problem that producers are faced with is known as *decision making*. Let $\Delta_{t+l|t}$ be the decision that a generator/supplier is called to make at time t for a lead time $t+l$. A key point for the supplier/generator is to identify the lead time $t+l$ of the decision. The choice of l classifies the decision into two main categories: operational and strategic. As stated in [15], operational decisions are those where the best action is made for given resources in order that some undesirable result is to be avoided. In contrast to operational decisions, strategic decisions dictate the optimum action with respect to the expected distribution of future events.

This paper focuses on strategic decision making for trading wind power in electricity markets where there is a given level of uncertainty in the wind power forecasted. According to [2], strategic decisions are classified as *long*, *medium* and *short-term* depending on the time-frame. Therefore, the purpose of the forecast differs depending on the time-frame. For instance, in the case of *long-term decisions* we refer to the future planning of power plants. *Medium-term* decisions are applied to fuel purchases and bilateral or physical contracting while *short-term* decisions are mainly made for bidding in the short-term, e.g. power exchange markets and for establishing an hourly production schedule. In the literature, several approaches for making optimal decisions are presented. *Zadeh* in [18] explained the differences between possibility and probability theories. He also stated that uncertainty, which is a by-product of randomness, can be dealt with using methods such as fuzzy set theory rather than probability theory. *Massucco et al*. also concluded in [12] that the use of a deterministic method for dealing with problems which contain stochastic variables is rather poor and insufficient. Therefore they proposed a technique which combines fuzzy logic and deterministic approaches for generating strategic bidding in an electricity market. In [16], a tool based on an MDP (Markov Decision Process) is applied for finding the optimum bidding strategies from the generator's point of view in a market similar to NETA. In this study *Song* *et al*. pointed out that it is possible that the future market or even the IPP's placement in the future market can be influenced depending on the strategy selected.

Section 3 below provides a description of the functionality of a preliminary tool for *medium-term* decision making.

3 PROPOSED DMT

PROVIDEO, is a decision making tool which is under development at the Centre for Renewable Energy Systems Technology (CREST), UK. Its name is borrowed from Latin since according to [6] it means *to see before*, *to foresee*, *to consider in advance*. The aim of developing this tool is to solve a *medium-term* decision making problem and hence its function is optimizing the trade of bilateral or physical contracts between wind generators and suppliers.

The functionality of PROVIDEO depends on several sets of input data including:

- Past observed weather data;
- Past forecast weather data;
- Past wind farm power production data;
- Past trading decisions;

These data are specific to the wind farm sites for which electricity production is to be traded. Past forecast data can be based on the output of combined statistical/physical models for time horizons up to around 10 days. Above 10 days, forecasts are based on pattern recognition analogue forecasts which is an additional module within the PROVIDEO software. Alternatively, long term forecasts from other available models may be used as input.

PROVIDEO contains a number of modules in order to take input data and turn this into a trading decision as shown in Figure 1. The first two modules form part of the initially model training:

- **Classification**: Initially past observed weather data and past forecast data are analysed statistically using methods such as Analysis of Variance (ANOVA) to determine the dependence of forecast accuracy over different time horizons as a function of climate and other parameters, e.g. wind speed range, temperature, pressure, time of day, season, etc. This is used to determine a number of forecast uncertainty classes which indicate the expected level of accuracy for a particular forecast under a particular set of conditions. This is done as a one-off process but does allow for refinement of the classes over time as more historical data becomes available.

- **Power Transfer Function**: A comparison is made between past historic weather data and past historic generation to determined the transfer function between wind speed and wind farm output. This is essentially the construction of a wind farm power curve which can take as input parameters turbine and grid availability, etc.

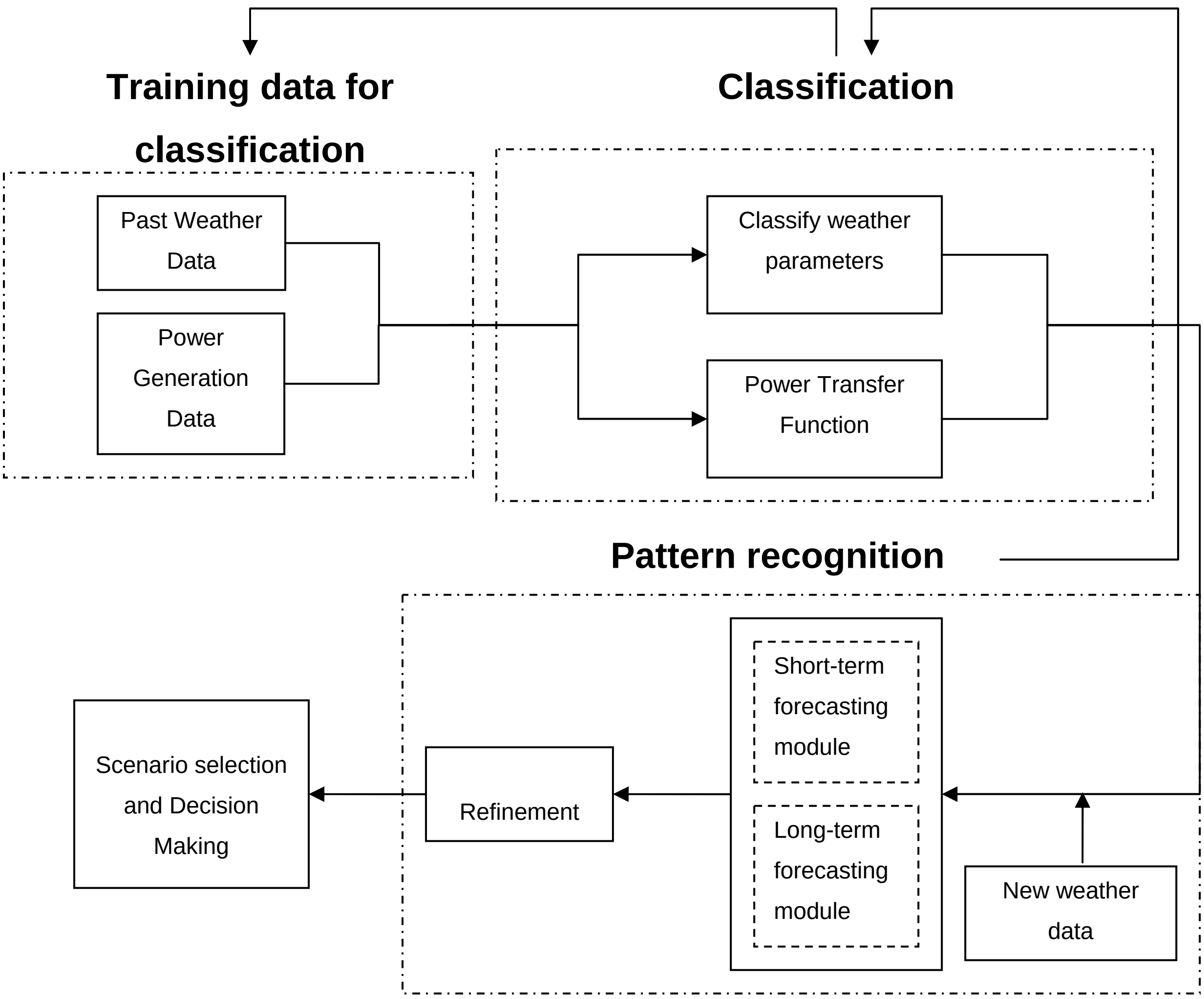


Figure 1: Schematic representation of PROVIDEO

As mentioned above, short term forecasts (up to around 10 days ahead) are assumed to be available as input from an appropriate statistical/physical model. PROVIDEO provides a module for forecasting further ahead:

- **Long-term forecasting module**: Longer term forecasts of wind speed (up to three months ahead) are made using an analogue forecasting model. Trends based on similar repeating patterns of meteorological parameters in the past are used to forecast ahead. To do this, data are suitably sub-divided by month and pattern recognition is used to produce the best forecast ahead depending on the best match to historical weather patterns as well as an indication of expected forecast uncertainty.

The next modules use the classes and transfer function as detailed above in the on-line generation of trading decisions:

- **Pattern Recognition**: As new forecasts become available, their best fit to the forecast uncertainty classes is determined;
- **Refinement**: Based on the classified forecast and power transfer function, an envelope of wind farm production scenarios is developed;
- **Decision Making**: The optimum trading decision is made based on the envelope of production scenarios, market prices and past trading decisions;

The most common problem in decision making under uncertainty is that information is vague and ambiguous or “fuzzy”. Therefore the selection approach used in the Decisions Making module is based on fuzzy information multi-objective decision making.

As mentioned above, it has been said that the rules of the market or the decision that the IPP will make, can influence their future placement within the market. Prices of electricity and fuels are additional parameters which can play an important role in a decision. PROVIDEO, by using a multi-objective decision making module, evaluates how well each alternative or scenario satisfies each objective e.g. minimising imbalance costs, maximizing profit, securing system operation, etc. The different objectives can be appropriately weighted and combined in a decision function in order that an optimum decision can be made.

4 CONCLUSIONS

While probability theory is related to the likely frequency of an event happening, possibility theory is related to the degree of feasibility that each event will occur. A decision making tool for the optimal trading of wind farm production is presented in this paper. The DMT called PROVIDEO is based on possibility theory and multi-objective fuzzy decision making. The tool depends on site specific past information associated with the weather as well as generation and provides users with the optimum trading decision at a given time. Future work will present the first results from PROVIDEO.

BIBLIOGRAPHY

[1] G. N. Bathurst, J. Weatherill, and G. Strbac. Trading wind generation in short term energy markets. *IEEE Transactions on Power Systems,* vol. 17, issue: 3, p. 782, 2002.

[2] E. Centeno, J. Reneses, and J. Barquin. Strategic analysis of electricity markets under uncertainty: a conjectured-price-response approach. *IEEE Transactions on Power Systems,* vol. 22, issue: 1, p. 423, 2007.

[3] A. Costa, A. Crespo, J. Navarro, G. Lizcano, H. Madsen, and E. Feitosa. A review on the young history of the wind power short-term prediction. *Renewable and Sustainable Energy Reviews,* vol. 12, issue: 6, pp. 1725-1744, 2008.

[4] EC. Directive 2001/77/EC of the European Parliament and the Council on the promotion of electricity produced from renewable energy source in the internal electricity market. 2001.

[5] G. Giebel, L. Landberg, G. Kariniotakis, and R. Brownsword. State-of-the-art on methods and software tools for short-term prediction of wind energy production. In *Proceedings of the European Wind Energy Conference and Exhibition*, *EWEC'03, June 16-19, Madrid, Spain*, 2003.

[6] P. G. Glare. *Oxford Latin Dictionary*. Glare, P. G., 1982.

[7] I. Kuzle, D. Bosnjak, and S. Tesnjak. An overview of ancillary services in an open market environment. *15th Mediterranean Conference on Control and Automation,* issue: p. 22, 2007.

[8] L. Landberg, G. Giebel, H. A. Nielsen, T. Nielsen, and H. Madsen. Short-term prediction - An overview. *Wind Energy,* vol. 6, issue: 3, pp. 273-280, 2003.

[9] L. Landberg, S. J. Watson, J. A. Halliday, and J. Jørgensen. Short-term prediction of local wind conditions. In *Proceedings of the European Wind Energy Conference and Exhibition*, *EWEC'93, March 8-12, Travemünde, Germany*, pp. 677-680, 1993.

[10] R. Madlener and M. Kaufmann. Power exchange spot market trading in Europe: theoretical considerations and empirical evidence. 2002.

[11] I. Marti, G. Kariniotakis, P. Pinson, I. Sanchez, T. S. Nielsen, H. Madsen, G. Giebel, J. Usaola, A. M. Palomares, R. Brownsword, J. Tambke, U. Focken, M. Lange, G. Sideratos, and G. Descombes. Evaluation of advanced wind power forecasting models - Results of the ANEMOS project. In *Proceedings of the European Wind Energy Conference and Exhibition*, *EWEC'06, 27/2 - 2/3, Athens, Greece*, 2006.

[12] S. Massucco, L. Meini, F. Silvestro, G. Burt, S. Galloway, J. McDonald, and T. Siewierski. Electricity market strategy characterisation with fuzzy logic: application to different types of power plants. *2004 International Conference on Probabilistic Methods Applied to Power Systems (IEEE Cat. No.04EX853),* issue: p. 61, 2004.

[13] P. Pinson, C. Chevallier, and G. N. Kariniotakis. Trading wind generation from short-term probabilistic forecasts of wind power. *IEEE Transactions on Power Systems,* vol. 22, issue: 3, pp. 1148-1156, 2007.

[14] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol. A survey of frequency and voltage control ancillary services-part II: economic features. *IEEE Transactions on Power Systems,* vol. 22, issue: 1, pp. 358-66, 2007.

[15] T. J. Ross. *Fuzzy logic with engineering applications*. Chichester : Wiley, 2004.

[16] H. Song, R. W. Dahlgren, C.-C. Liu, and J. Lawarree. Optimal electricity supply bidding by Markov decision process. *IEEE Transactions on Power Systems,* issue: 2000.

[17] S. J. Watson, L. Landberg, and J. A. Halliday. Application of wind speed forecasting to the integration of wind energy into a large scale power system. *Proceedings of the IEE in Generation, Transmission, and Distribution.,* vol. 141, issue: 4, p. 357, 1994.

[18] L. A. Zadeh. Possibility theory vs. probability theory in decision analysis. *Proceedings of the 1977 IEEE Conference on Decision and Control,* issue: p. 9, 1977.

[19] A. Zervos. Developing wind energy to meet the Kyoto targets in the European union. *Wind Energy,* vol. 6, issue: 3, pp. 309-319, 2003.

Dynamic Security Assessment Considering High Penetration of Dispersed Generation

Chris Oliver Heyde

Otto-von-Guericke University Magdeburg, Germany

ABSTRACT

Power Systems have to face rapid changes. The deregulation, the growth of dispersed generation and the growing interconnected power systems lead to operating situations close to their security and stability boundaries. The system operators are confronted with more unknown and unusual situations to which they have to respond the right way. In this paper a system is introduced to help the operator to judge the severity of a situation on the one hand and to give recommendations for the right decisions on the other hand.

KEYWORDS

DSA, integration of dispersed generation, voltage stability.

1 INTRODUCTION

A dynamic security assessment system is introduced in this paper which is currently being developed. The aim of this online working system is to calculate the current system state, considering selected contingencies, and its security margins. Possible preventive or remedial measures in case of oncoming insecurity should be analyzed in advance and be given to the operator as an advise. The strong stochastic behaviour of wind power generators is responsible for the high degree of unusual and unknown system states. This is the reason why precise wind forecasts have to be considered in the scenario builder of the proposed system.

The whole system is divided into the data acquiring part (pink) and the simulation part (green boxes). In order to concern for all the mechanisms that lead to insecurity of the power system, different models are simulated in different modules. For example, voltage stability calculations require more detailed load models as small signal or transient stability calculations. In addition the modularization makes it possible to parallelize the work in order to reduce computation time.

Each module is calculating one or more stability indices which are weighted and reduced to one single index to be presented to the operator. After an insecurity is identified, the operator can easily decide what happened by accessing the individual indices.

chris.heyde@ovgu.de

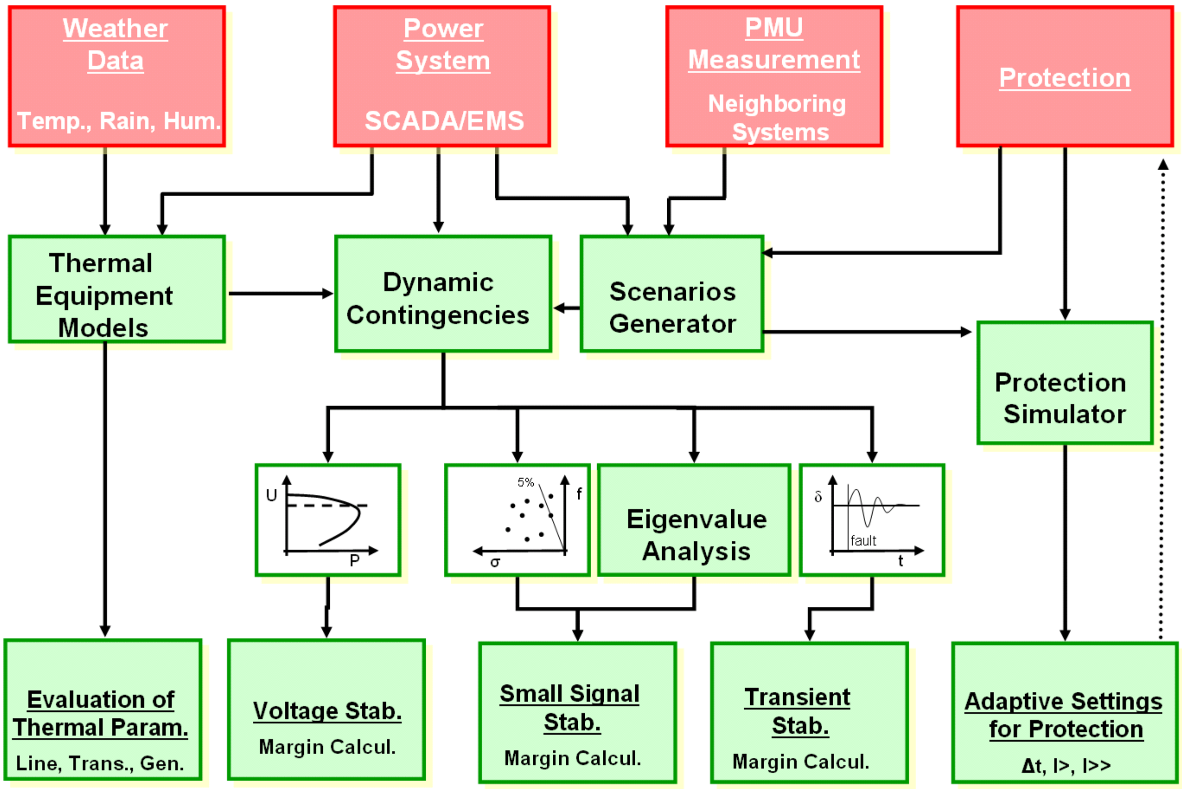


Figure 1: Structure of the dynamic security assessment system.

2 CONCLUSIONS

Changes in use and operation of the transmission systems, driven by deregulation and energy trading, will bring the electrical systems to their thermal, stability and protective limits. This will require in future tools for online security assessment to give the operator information about the margins from the actual point of operation to points of outage and collapse. The protection system must be considered during all system calculations and simulations to cover possible margin reductions by installed relays. Hereby, necessary countermeasures must be defined and pre-checked to find the most suitable measure if a contingency will occur in the actual point of operation. The most appropriate countermeasures can now be provided by the DSA system immediately after a disturbance is actually recognized by the system. This is one of main advantages of online dynamic security assessment systems because the operator can use the time of usually only few minutes to decide instead of finding a solution. This system will also contribute to a better integration of wind power, because the influence of high wind power penetration on the security level of the power system will be analyzed online during network operation.

The Role of Wind Power Forecasting and Innovative Concepts in the Integration of DG/RES

Ümit Cali

ISET e.V. – University of Kassel

ABSTRACT

The aim of this PhD study is to investigate the role of wind power forecasting and the other innovative concepts in the integration of DG/RES. Current market interactions between DG/RES Operators and other actors and existing support schemes in Europe are examined in order to analyse the benefits of innovative network integration options. The Multi-NWP approach has been performed to investigate the influence of merging different NWP models on the accuracy of the wind power forecast. Beside wind power forecasting, other innovative integration concepts like energy storage systems, new energy management and control strategies will be investigated. Finally, energy economic analysis of wind power forecasting and energy storage will be performed.

KEYWORDS

Wind Power, Forecasting, Distributed Generation, Renewable Energy Sources, Integration, Artificial Neural Networks

1 INTRODUCTION

Electricity generated from renewable energy sources will be more important in the future energy supply in many countries. Large scale deployment of renewable electricity supplies, especially wind power, requires well structured innovative network integration concepts. Wind power prediction plays a very important role to improve the economical and technical integration of a large share of wind energy into an existing electricity grid. In the scope of the PhD. study wind power forecasting is investigated in detailed. In order to improve the accuracy of wind power forecasting a new approach based on multi model approach is developed. Finally, utilization of intraday trading and energy economical benefits of wind power forecasting is analyzed.

2 GRID INTEGRATION AND INNOVATIVE INTEGRATION CONCEPTS

Wind power and PV with their variable and intermittent (PV) output characteristics affect the other generators in the system.

uecali@iset.uni-kassel.de

In order to overcome the problems caused by intermittent RES, it is necessary to develop advanced integration solutions like distributed real-time monitoring and controlling systems, active network management, energy storage and wind power forecasting system. A review of most promising innovative network integration concepts for RES is performed in order to analyse the role of these innovative options. Subsequently, wind power forecasting is dealt more detailed and quantitatively with from two points of view: network controllability for the TSO and balancing market functioning.

3 INTEGRATION OF RES USING WIND POWER FORECASTING

3.1 Wind Power Forecasting

The fluctuating and intermittent behavior of wind power generation leads to challenges for the operation of the power system. Forecasting of the expected wind power generation plays a key role in this respect to integrate intermittent sources such as wind and solar power efficiently into the existing electricity system. The aim of a wind power forecast is to estimate the expected generation of wind power from one or more wind turbines (referred to as a wind farm or cluster).

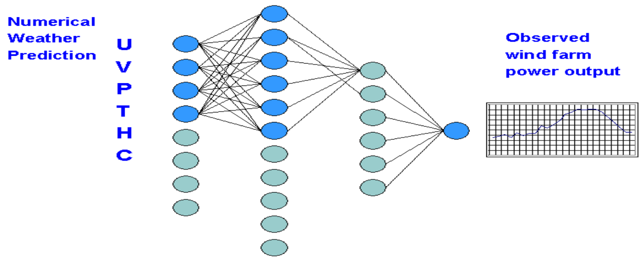


Fig 1. The sketch of an artificial neural network (ANN) used for wind power forecasting

For the purpose of learning the relationship between meteorological data and wind farm power output, the ANN needs to be trained with numerical weather forecasts and measured power values from the past. [2], [5]

3.2 Improvement of Wind Power Forecasting using Multi Model Approach

The multi model approach, which is covered in this study, consists of two main methods:

- The Multi-NWP (Numerical Weather Prediction) approach, combining the predictions of several different NWP models, typically from different providers
- The Multi-scheme ensemble weather prediction system (MS EPS) approach, utilising the predictions of different members of the MS EPS, typically from one provider

The aim of the Multi NWP approach is to investigate the influence of merging different NWP models on the accuracy of the wind power forecast. The use of a multi-scheme ensemble weather prediction model (MS EPS) to improve the accuracy of wind power forecasting is investigated as an alternative to the costly combination of different numerical weather prediction (NWP) models. [1], [3], [4]

3.3 Utilization of Intraday Trading and the Benefits of Wind Power Forecasting

It is obvious that, the short-term forecasts of wind power have significantly higher qualities than day ahead forecasts. On the other hand, it does not mean that the short-term wind power forecasts should be replaced with the day ahead forecasts but they should supplement the day ahead forecasts. The short-term forecast error is balanced in the minute reserve, and the deviations between the short-term and the day ahead wind power forecast errors are compensated in the long-term hour reserve. Without deploying the intra-day market, the deviation between real and the forecasted wind power values needs to be balanced during the operational control by the control reserve. Energy economical benefits of wind power forecasting will be analyzed in the German power market (EEX) as the final part of the study.

4 CONCLUSIONS

Identification of innovative network integration options for DG/RES gives us to discover potentials of the future application areas in order to integrate large amounts of RES into the existing grid.

After reviewing of the most promising innovative concepts qualitatively, a more detailed quantitative analysis is done on wind power forecasting. Therefore, different approaches are investigated with the aim to reduce the wind power forecast error. As a first approach, three independent numerical weather prediction (NWP) models are used in ISET's artificial neural network (ANN) based forecasting system to perform wind power forecasts for the whole of Germany. Already a simple averaging reduces the RMSE by about 20%.

As an alternative to the use of independent NWP models, the use of a multi-scheme ensemble prediction system (MS EPS) is investigated. The use of the averaged weather data (EPS-MEAN) leads to a clear reduction of the RMSE for one of the investigated wind farms, while for the other wind farm the resulting forecast is not better than that of the best single member of the ensemble.

Finally, the utilization of Intraday trading and the energy economical benefits of wind power forecasting is investigated.

BIBLIOGRAPHY

[1] Cali, Ue.; et al. Artificial Neural Network Based Wind Power Forecasting using a Multi Model Approach, 7th International Workshop on Large Scale Integration of Wind Power on Transmission Networks for Offshore Wind Farms, Madrid, 2008

[2] Cali, Ue.; et al. Short-term Prediction of Distributed Generation- Recent Advances and Future Challenges, 11th Kasseler Symposium Energy Systems Technology, Kassel, 2006

[3] Lange B., Rohrig K., Ernst B., Schlögel F., Cali Ue., Jursa R., and Muradi J., ;Wind Power Forecasting in Germany-Recent Advances and Future Challenges. in Zeitschirift für Energiewirtschaft, vol. 30, no. 2 pp.117-122.

[4] Cali Ue., ; et al. Artificial neural network based wind power forecasting using a multi-scheme ensemble weather prediction model, presented at the EWEC, in Proceeding, 2008, Brussels

[5] Ernst B.; et al. Predicting the Wind, IEEE Power & Energy Magazine, pp. 78- 88, November/December 2007.

Non-parametric system identification of an offshore wind turbine structure

Thomas Pahn, Raimund Rolfes, Wolf-Jürgen Gerasch

Institute for Structural Analysis, Leibniz Universität Hannover, Germany

ABSTRACT

The sizes of dynamic loads on offshore wind turbines (OWT) are essential for the design of the load carrying structure. For that reason realistic determination of these loads is necessary for a secure and economical design. Within the research project OGOWin the Institute for Structural Analysis in Hannover deals with the optimisation of a foundation structure for an OWT due to dynamic forces. Therefore the so called jacket structure is modelled with FE. By means of in situ measurements of the structural dynamic behaviour a validated FE-Model will be created. This realistic model allows for determining the wind and wave loads via an inverse method.

KEYWORDS

Offshore wind turbine, load estimation, system identification, inverse method, structural optimisation

1 INTRODUCTION

Determining factors for designing OWT structures are given by dynamic loads. Hence, knowledge of real load values allows for cost-efficient design. Determination of these loads requires a realistic model which can be generated by means of system identification methods [1]. The described research project deals with the optimisation of a REpower 5M prototype structure [Figure 1], that serves as basis of a serial fabrication for OWT foundations drafted for water depth of about 30 m and coast distances up to 40 km.

Figure 1: REpower 5M prototype, Bremerhaven, Germany

t.pahn@isd.uni-hannover.de

2 NUMERICAL WORKSTEPS

The research process is divided into four main steps namely “FE-modelling”, “measurement”, “validation” and “inverse calculation”. All single steps will be described below.

The initial stage of the research project puts special emphasise on creating the FE-model. It serves for describing the structural behaviour. Consequently, it gives ideas about natural frequencies and modes. In this way the FE-model represents the basis for the non-parametric system identification.

Normally calculated and measured eigenfrequencies do not match. For that reason an adjustment of the FE-model to the real dynamic behaviour is necessary. As validation method the correction of the stiffness matrix K [1] is used. This iterative procedure depends on the definition of sensitive sub-matrices that will be factorized by correction parameters. Those sub-matrices for example can represent uncertain model attributes such as soil parameters. For the definition of the sub-matrices sensitivity analyses have to be performed.

3 NON-PARAMETRIC SYSTEM IDENTIFICATION

For a clear identification of natural vibration values artificial test functions will be used to induce free vibration of the structure. By FE-analyses a measurement concept has been defined. As test functions sweep excitation as well as step function are ascertained to excite the 120 m high OWT. The objective is to determine local and global vibration characteristics. Moreover, information concerning aerodynamic damping is expected. By means of FE-simulation feasibility and dimensioning of required excitation forces as well as position of excitation have been set. In that way adequate sizes of response values for instant accelerations and strains are assured.

4 CONCLUSIONS

Current state of the research implies the FE-modelling including parameter studies and sensitivity analyses. Furthermore the applicability of the chosen validation method could be shown. By the help of FE-simulation the measurement concept has been arranged. Focus of further work will lie on executing and interpreting measurements at the real structure. Afterwards the validation will be realised. As a result reality describing system matrices can be extracted. The generated real model can be used in combination with measured system responses due to natural excitation. Via an inverse calculation real load values will be determined.

BIBLIOGRAPHY

[1] Natke: “Einführung in die Theorie und Praxis der Zeitreihen- und Modalanalyse”. Vieweg & Sohn. Braunschweig / Wiesbaden.1983.

Opportunities for the Superwind concept

Integrating wind energy with hydrogen producing fuel cells.

A. L. Vernay[1], K. Hemmes[1], Diederick Manné[1] & Gijs Steenvoorden[2]

[1] Technical University of Delft, The Netherlands; [2] PG-ID, The Netherlands

ABSTRACT

It is well known that renewable energy sources, especially wind energy (and solar energy) have a fluctuating character, which makes it difficult to match with practical demand. The often proposed solution for this problem is the conversion of the surplus of wind energy into hydrogen by means of electrolysis. The Superwind concept offers a more efficient alternative for integrating wind energy into the grid. It consists of the integration of a wind turbine with an internal-reforming fuel cell (MCFC or SOFC) capable of co-producing hydrogen and electricity. The main advantage of this multi-source multi output system lies in its high degree of flexibility. Peaks in wind energy production can be compensated by a decrease in electricity production from the fuel cell. Contrary to other electricity production units the fuel cell does not stand idle when compensating for peaks in wind energy, but instead will be producing hydrogen.

Moreover, this system is also been considered as a tool towards the development of a hydrogen infrastructure.

KEYWORDS

Wind turbine, fuel cells, multi source multi product system, hydrogen

1 INTRODUCTION

It is well known that renewable energy sources, especially wind energy and solar energy have a fluctuating character and are hard to predict accurately. This can lead to different problems depending on which perspective we are looking at. From a transmission grid perspective, large scale integration of wind energy can cause grid congestion and increases the need for reserve and balancing production capacity. However, from the wind turbine owner perspective, the problem is quite different. When the amount of electricity produced does not match the amount of electricity sold on the market, the turbine owners have to pay for the so-called balancing costs. This limits the economics of wind turbines. The superwind concept represents an innovative solution to reduce these balancing costs and better integrate wind turbine into the grid.

a.b.h.vernay@tudelft.nl

Superwind consists in the integration of a wind turbine with an internal reforming fuel cell, for the flexible co-production of power, hydrogen and heat.

2 TECHNICAL FEASIBILITY: INTERNAL REFORMING FUEL CELL, FLEXIBLE ENERGY PRODUCTION UNITS

In its original form, the superwind concept consists of an internal reforming fuel cell (either solid oxide fuel cell or molten carbonate fuel cell) with natural gas or biogas as input, which is internally converted into hydrogen. In the endothermic reforming reaction, heat from the fuel cell is converted into chemical energy. It has been calculated that in normal operation, sufficient heat is produced by the fuel cell to convert more natural gas into hydrogen than necessary for its own consumption. Thereby the fuel cell is able to produce a surplus of hydrogen [1-3].

Moreover, because the heat can be used efficiently in the reforming process of natural gas, one is able to operate the fuel cell at higher power density. In this mode, the efficiency is decreased, so more heat is produced, but that heat is now efficiently converted into hydrogen.

In this way a very flexible system is obtained in which the standard high-efficiency operation of the fuel cell with no or little hydrogen production can be changed into a high-power operation mode in which about double the power output can be obtained with, on top of that, almost the same (double) power output in the form of hydrogen. Apart from the four times higher output of high quality energy products (electric power and hydrogen) system introduces production flexibility. This flexibility can be used to match fluctuations in the wind or solar power. By operating the fuel cell in a complementary way to the power produced by the wind turbine (or the solar panels) a more or less constant power output can be obtained (see Figure 1) [4].

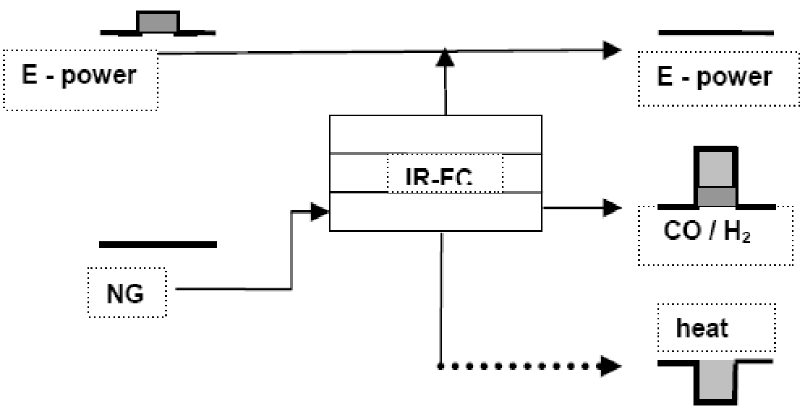


Figure 1: integrated energy system using the flexible co production of hydrogen and power of an internal reforming fuel cell to compensate fluctuating supply of renewable energy [4].

In operating the fuel cell one has the flexibility to produce more or less (or no) hydrogen depending on the demand for this product. This gives the possibility to adapt to a growing market for hydrogen. Moreover, in the concept, the electric power from the wind turbine (or solar panels) is always completely delivered to the grid or consumed locally. It is very important to understand that in the superwind concept no conversion of electric power from the wind turbine and subsequent storage of any form of energy is taking place nor necessary. The operating principle is totally derived from the flexibility in producing electric power and/or hydrogen from the fuel cell and the already available energy storage capacity of natural gas (or biogas). No additional storage is necessary.

3 ECONOMIC FEASIBILITY

We have just described the technical feasibility of superwind. However, for an idea to be implemented it should also be economical. Studying the economic feasibility of the superwind is rather complex. Indeed, it is dependent on many variables: Capital expenditure, operation expenditure, price and market for our products (electricity, hydrogen and heat), balancing costs, and fuel cell operation strategy etc. We have performed a number of calculations based on one year data (2007) and preliminary results show that with a fuel cell cost of 900 €/kW, the system can be economically feasible. Economic feasibility is here described as having a payback time of 5 years and a return on investment (ROI) of 10%.

4 CONCLUSIONS

Superwind is an efficient and innovative solution for combining wind turbine and fuel cells. Moreover, we have shown that superwind can be economical feasible if fuel cell costs are decreased below 100 €/kW. However, as holds for operating on the stock markets; results obtained in the past are no guarantee for the results to be obtained in the future. So a larger data set yields a better average of the past and what the performance of the superwind concept would have been, but it does not necessarily provide a better prediction of the future market performance. If implemented on a larger scale, superwind should help better integrate wind electricity to the grid by decreasing fluctuation and improving predictability. However, the actual added value may be difficult to quantify.

BIBLIOGRAPHY

1. Hemmes, K., Fuel cells in Modern Aspects of Electrochemistry ed. RE White, BE Conway and CG Vayenas. Vol. 37. 2004, New York: Kluwer Academic/Plenum Publishers. 131-251.

2. Leal, E.M. and J. Brouwer, Thermodynamic analysis of production of hydrogen using high-temperature fuel cells. Proceedings of the Asme Advanced Energy Systems Division, 2005. 45: p. 481-490.

3. Leal, E.M. and J. Brouwer, A thermodynamic analysis of electricity and hydrogen co-production using a solid oxide fuel cell. Journal of Fuel Cell Science and Technology, 2006. 3(2): p. 137-143.

4. Hemmes, K. A novel integrated wind and natural gas energy system. in 6th International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms. 2006. Delft, The Netherlands.

A Fresh Wind Is Blowing For Rural Electrification - Development Of A Small Wind Turbine Concept For Rural Electrification

Paul Kühn[1)]

[1)] ISET e. V., Königstor 59, D-34119 Kassel, Germany

ABSTRACT

The objective of this PhD project is to develop a concept of a small wind turbine in the kilowatt range, specifically for the electrification of rural areas. A design method is being elaborated that considers jointly the latest technical developments as well as experiences with low-tech approaches. Moreover, socioeconomic aspects, local conditions and infrastructural needs are analyzed.

The contribution gives an overview of the work carried out so far. Additionally, the question is discussed whether there is an alternative solution to brushes and slip rings in order to transmit electricity through the rotating yaw bearing of horizontal axis small wind turbines.

KEYWORDS

small wind turbine, rural electrification, wind turbine design

1 INTRODUCTION

Small wind turbines (SWTs) have an enormous potential to cover a considerable portion of the electrical power required in developing countries. The market for SWTs is complex and offers a variety of SWT-types with different technical concepts. However, the available SWTs are not geared exclusively to the future markets in developing countries. Therefore they do not provide optimal solutions for systems for rural electrification, i. e. isolated (hybrid) power systems, local mini-grids etc. Thus, the key question is this: What is the adequate technology for a SWT-system to become widely used in developing countries?

Technical and socioeconomic aspects are taken into consideration in order to find a solution to this multi-disciplinary problem. The project draws from ISET know-how and refers to data from previous projects. Furthermore, an autonomous experimentation hybrid system in the ISET test field is used for the implementation and testing of the concept.

pkuehn@iset.uni-kassel.de

2 APPROACH

In the first stage of the project the SWT market was studied, different SWT concepts and their applications were investigated and operational experience with SWT systems was analysed, see [1]. After that, system requirements and operating conditions for the SWT application 'rural electrification' were identified. These include low costs, simplicity and high reliability as well as flexibility regarding system integration and maximum local involvement with respect to production and operation. Moderate wind resources, a poor accessibility of isolated communities and a lack of trained service personal are to be mentioned as examples of challenging operating conditions.

The current focus is on the adequacy of different topologies and design features for the SWT concept to be developed, e. g. rotor axis, number of rotor blades, type of generator, control system and tower type among others. In the next section such a design problem is illustrated by the example of an alternative solution for the electricity transmission through the rotating yaw bearing of horizontal axis SWTs.

3 SLIP RINGS OR NO SLIP RINGS

Most horizontal axis SWTs feature brushes and slip rings to transmit electricity through the rotating yaw bearing. Only a few manufacturers of SWTs and home build machines, e. g. [2], use power cable twist for reasons of cost and simplicity (see Figure 1). Reliability is another reason why the cable twist design might be an alternative to brushes and slip rings. Evaluations on reliability of SWTs in Germany show a promising low frequency of failure, with complex design features generally resulting in an impairment of reliability [1]. If one decides for a horizontal axis design, the task is to weigh cost, reliability, maintenance requirements and safety etc. of both alternatives against another, i. e. brushes and slip rings versus cable twist.

Figure 1: Cable twist on a small wind turbine without slip rings

In order to assess both options, particular attention is paid to the cable twist design as there is not much information and literature on this topic. The first question that needs to be addressed is how much cable torsion is to be expected over time? Simulations based on long-term wind measurements in Germany indicate that the torsion of the cable would be manageable if regular maintenance is performed to untwist the power cables, e. g. every six or twelve months. To verify this, wind data of other regions of the world and operational data of SWTs using cable twist must be analysed.

Additionally, the effects and consequences of a cable twist design need to be studied more deeply so as to answer further relevant design questions like: What is the maximum load on the cables? What are the required cable properties? What is the influence of yaw stiffness and horizontal furling on cable twist? What safety options exist to prevent cable over-twist?

4 CONCLUSIONS

The project presented here studies different SWTs designs and explores a concept SWT especially for applications in rural regions of developing countries. State of the art technology as well as low-tech approaches are used and, where appropriate, combined to satisfy requirements like low cost, high reliability, local involvement and easy operation and maintenance.

A simplistic design accepting a power cable twist as an option to transmit electricity through the rotating yaw bearing of horizontal axis SWTs is discussed in more detail. First results indicate that the cable torsion is manageable and would not lead to excessive maintenance. Further work will show whether this design is an adequate alternative to the popular brushes and slip ring concept used in SWTs in the kilowatt range.

BIBLIOGRAPHY

[1] P. Kühn: Big Experience with Small Wind Turbines – 235 Small Wind Turbines and 15 Years of Operational Results, EWEC 2007, Milan, May 2007

[2] H. Piggott: How to build a wind turbine – The Axial flux windmill plans, Scoraig Wind Electric, June 2005

Wind Energy Applications in the Built Environment

Christina Beller

Risø DTU, Denmark

ABSTRACT

Besides wind farms off- and on- shore, there is a potential in city wind. The energy losses by transportation from the location of energy generation to location of energy consumption might be calculated against the lower efficiency of small wind turbines. Wind energy can contribute to the on- site power supply and support for example solar energy systems. Furthermore, awareness of energy usage will be carried into the city environment. An idea catalogue of possible applications will be the outcome of discussing the special boundary conditions in the built and inhabited area.

KEYWORDS

Urban Wind Energy, Small Scale Wind Energy

1 INTRODUCTION

Wind energy in the built environment is getting more popular, since energy costs are rising. Besides this fact, architects are interested in integrating wind turbines in buildings structure. A general demand has motivated to look into the small scale wind energy in inhabited areas.

2 CONDITIONS

2.1 Wind

First of all, the available wind is depending on the location of the city. Copenhagen, for example, is situated close to the sea side and therefore high mean velocities are entering the built environment. Furthermore, the location within the city is of importance, to regard the roughness change (Fig. 1).

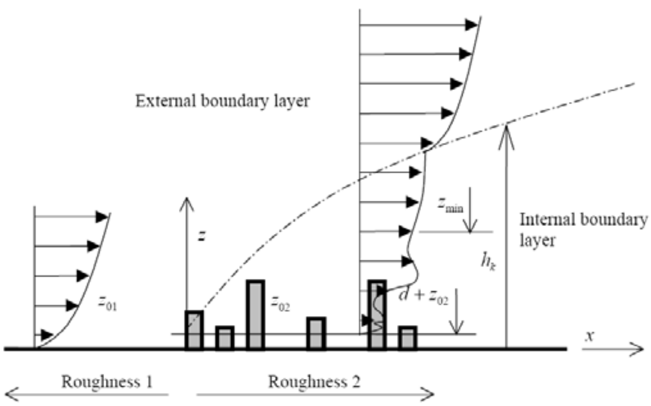


Fig. 1: Boundary layer profile change due to a step in roughness height [1]

christina.beller@risoe.dk

After that, the neighbourhood is influencing the wind conditions, by e.g. streets aligned to the mean wind direction, parks bordered by trees and bushes, rivers or lakes with low surface roughness and the average buildings height. From this macro scale wind climate, the next zoom is on the micro scale wind climate around structures, in case of integrated wind turbines. In general, city wind is lower and more turbulent than wind on the open field.

2.2 Noise and Vibrations

Besides living greener, the trend goes to keep the home bright and quiet. Noise from turbines and shadow cast needs to be prevented. Aero- acoustical noise emission is proportional to the fifth power of the tip speed [1]. The vibrations induced by rotating devices needs to be higher than the eigenfrequencies of the supporting structure (e.g. roof, walls, mast).

2.3 Safety

In dense populated areas, the probability of mortal impact is higher than on an isolated side. Safety factor needs to be higher and casings, materials and structural layout reconsidered.

3 APPLICATIONS

The discussion of turbines integrated in buildings and small turbines on already existing buildings with their pros and cons [2] brought the focus on less dependent applications to enter the urban space. The energy shall be used directly, not vanishing in the grid, and for all the citizens benefit, while the design is simple, unobtrusive and save in Copenhagen's public.

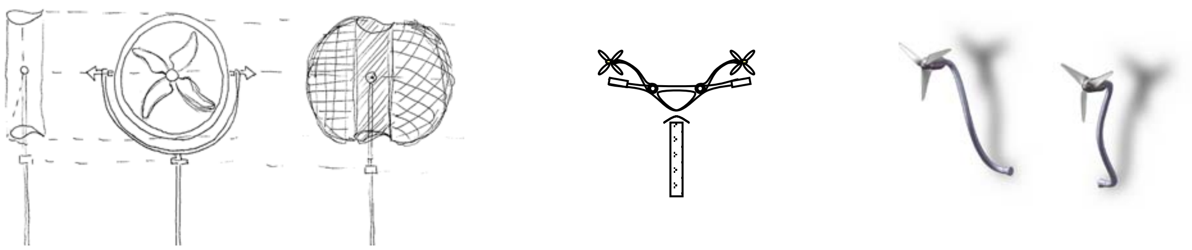


Fig. 1: Sketches of small scale wind turbine/ applications

4 CONCLUSIONS

The issues to be looked at need more investigations. Wind conditions around structures will be analysed with the help of CFD simulations. The idea catalogue will be widened and one of the concepts put into action.

BIBLIOGRAPHY

[1] Mertens, S.; Wind Energy in the Built Environment; Multi- Science, 2006.
[2] Beller, C.; Urban Wind Energy; Risø- R- draft; May 2008

Load Extrapolation during operation for Wind Turbines

Henrik Stensgaard Toft [1),], John Dalsgaard Sørensen [1,2)]

[1)] Department of Civil Engineering, Aalborg University Denmark

[2)] Wind Energy Department, Risø DTU, Denmark

ABSTRACT

In the recent years load extrapolation for wind turbines has been widely considered in the wind turbine industry. Loads on wind turbines during operations are normally dependent on the mean wind speed, the turbulence intensity and the type and settings of the control system. All these parameters must be taken into account when characteristic load effects during operation are determined. In the wind turbine standard IEC 61400-1 a method for load extrapolation using the peak over threshold method is recommended. In this paper this method is considered and some of the assumptions are examined. The statistical uncertainty related to the limited number of simulations of the response during operation is explored together with the influence of the threshold value.

KEYWORDS

Wind Turbines, Load Extrapolation.

1 INTRODUCTION

In the wind turbine standard IEC 61400-1 [1] a method for statistical extrapolation of load effects is described. The method is based on [2] and uses the peak over threshold method. However, according to [3] the choices of threshold value and distribution function for the local extremes have a significant influence on the loading. In [4] it is indicated that the statistical uncertainty related to the limited number of simulations also has a significant influence on the load effect.

In the present paper the method for statistical extrapolation of loads is investigated with respect to the threshold value, the statistical uncertainty and the time separation. The time separation is applied in order to secure that the individual peaks are independent.

2 LOAD EXTRAPOLATION

The method used for load extrapolation is based on the peak over threshold method where a 3-parameter Weibull distribution is fitted to the local extremes at each mean wind speed.

hst@civil.aau.dk

The long-term distribution function for the global extremes is:

$$F_{long-term}\left(l\,|\,T\right)=\int_{U_{in}}^{U_{out}} F_{local}\left(l\,|\,T,U\right)^{n(U)}\; f_U\left(U\right)dU \qquad (1)$$

where $n(U)$ is the expected number of extremes at each mean wind speed U. $f_U(U)$ is the density function for the mean wind speed. U_{in} and U_{out} are the cut-in and cut-out mean wind speeds, respectively (typically 5 and 25 m/s).

The distribution parameters in the local Weibull distributions can be determined by the Maximum-Likelihood Method where the parameters become asymptotically normally distributed stochastic variables with expected value equal to the Maximum Likelihood estimators. The covariance matrix for the distribution parameters can be determined by the Hessian matrix of the Log-likelihood function. A more detailed description of the method for load extrapolation can be found in [5].

The characteristic response with a recurrence period on 50 years can be determined with and without statistical uncertainty, where the later is obtained using First Order Reliability Methods (FORM), see e.g. [6].

3 RESULTS

In the following the flap bending moment for a pitch controlled wind turbine is considered.

Table 1 shows the results for calculation of the response for nine different combinations of simulation time, threshold value and time separation. The simulation time indicates the number of 10 min. simulations and the threshold value is given in standard deviations above the mean. Time separation indicates the minimum time between independent peaks. Case 1 without statistical uncertainty is used as reference.

Table 1: Characteristic response – Flap bending moment, pitch controlled wind turbine.

Case	Simulations	Threshold	Time separation	Without statistical	With statistical
1	**25**	**1.4**	**10 sec.**	**1.000**	**1.045**
2	5	1.4	10 sec.	1.114	1.450
3	10	1.4	10 sec.	1.000	1.114
4	100	1.4	10 sec.	0.914	0.923
5	25	1.4	5 sec.	1.017	1.053
6	25	1.4	15 sec.	1.002	1.057
7	25	1.4	30 sec.	0.923	0.992
8	25	2.0	10 sec.	0.920	0.996
9	25	2.5	10 sec.	0.773	0.845

It is seen from table 1 that the statistical uncertainty has a significant influence on the load effect when the number of simulations is limited. The statistical uncertainty gives 30% extra load effect for 5 simulations and 4.5% for 25 simulations.

The characteristic load effect seems to decrease with longer separation time between the extremes, which can be due to the elimination of the lower extremes. The same tendency is seen for the threshold value, where a higher threshold value also leads to a decrease in the characteristic load. Both a longer separation time and a higher threshold value leads to less extremes and more statistical uncertainty.

4 CONCLUSIONS

In this paper load extrapolation during operation of wind turbines is investigated. Calculation of the characteristic response for nine different combinations of simulation time, threshold value and separation time show that the statistical uncertainty has a large influence on the loading for limited number of simulations. For longer separation time and a higher threshold value the characteristic response seems to decrease. This could indicate that the lower extremes are not representative for the long-term distribution. This effect should be studied further.

5 ACKNOWLEDGEMENT

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BIBLIOGRAPHY

[1] IEC 61400-1. Wind turbines - Part1: Design requirements. 3rd edition. 2005.

[2] Moriarty PJ, Holley WE, Butterfield S. Effect of turbulence variation on extreme loads prediction for wind turbines. Journal of Solar Energy Engineering-Transactions of the Asme 2002 Nov;124(4):387-95.

[3] Ragan P, Manuel L. Statistical Extrapolation Methods for Estimating Wind Turbine Extreme Loads. 45th AIAA Aerospace Sciences Meeting, 2007, p. 14553-71.

[4] Sorensen JD, Nielsen SRK. Extreme wind turbine response during operation. The Science of Making Torque from Wind. Journal of Physics, Conference Series, Vol. 75, paper 012074, August 2007.

[5] Toft HS, Sorensen JD. Reliability Analysis of Wind Turbines. 4th ASRANet International Collequium, 2008.

[6] Madsen HO, Krenk S, Lind NC. Methods of Structural Safety. Dover Publications, Inc.; 2006.

Wind Energy Research at the Department of Civil and Transport Engineering at NTNU

Karl Merz[1)]

[1)] Department of Civil and Transport Engineering, NTNU, Trondheim, Norway

ABSTRACT

This paper presents a brief overview of wind energy research in the Department of Civil and Transport Engineering at the Norwegian University of Science and Technology. In recent years research projects have been funded by a consortium between Norwegian industry and government, and the rate of investment is increasing. Interest is particularly high in offshore wind turbines, due to the difficulty of gaining the approval of local communities for installation of onshore wind turbines in coastal areas with high average wind velocities. The Department of Civil and Transport Engineering has a competence in offshore structures, due to a history of experience with offshore oil platforms. Current wind energy research in the department covers a breadth of topics related to structural loading and design.

KEYWORDS

structure, offshore, aerodynamic, control, truss, concrete, floating

1 INTRODUCTION

The Department of Civil and Transport Engineering at the Norwegian University of Science and Technology is actively involved in wind energy research, primarily under the lead of professor Geir Moe. There are currently three PhD candidates and one postdoc, with two more positions for PhD candidates recently opened for applications. This paper presents a brief overview of the current research topics.

Wind energy can be identified as one of the most promising renewable energy sources, both on grounds of economic viability and minimal environmental impact.[1] Coastal and offshore areas of Norway include some of the best wind environments, for purposes of energy production, in Europe.[2] The interest in offshore wind energy is especially strong, since local communities and environmental organizations tend to resist development of wind parks

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[1] Tester et al. [10]

[2] Moe [6]

karl.merz@ntnu.no

along the shoreline, citing concerns about aesthetics, noise, habitat preservation, and electromagnetic interference.[3]

The Norwegian government and industry have initiated research and development of this offshore wind resource.[4] While there is shallow water in the North Sea, much of the ocean off the Norwegian coast could be considered "deep" from the perspective of a wind turbine tower,[5] therefore one of the main engineering challenges is to develop cost-effective deep-water support structures, including floating platforms. (Worth particular mention is the development of two prototype, deep-water, floating offshore wind turbines of significantly different design, called HyWind and Sway, by the oil and energy company StatoilHydro.)

The Department of Civil and Transport Engineering at NTNU has a competence in offshore structures, based upon historical involvement in the development of offshore oil platforms, and is therefore well positioned to develop analysis techniques and structural concepts for offshore wind turbines. That being said, published studies on floating offshore wind turbines conclude that their economic performance is marginal,[6] therefore a direct application of oil platform technology will not work; less expensive solutions are required.

2 CURRENT RESEARCH ACTIVITIES

Wind energy research at the Department of Civil and Transport Engineering at NTNU covers a breadth of topics related to the design and analysis of wind turbine structures.

Professor Geir Moe leads the department's wind energy research activities. In addition to advising the work mentioned below, he has recently been involved in research on vortex induced vibrations of risers (pipes connecting the sea floor and a ship or platform at the surface), statistical analysis, and wind turbine performance.[7]

2.1 Support Structures

Haiyan Long is a PhD candidate; she is working on the design of a truss (jacket) tower, comparing its performance with a functionally equivalent tubular mono-tower, for an

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[3] The website http://www.miljovernforbundet.no/ presents arguments against coastal wind park development.

[4] Berntsen et al. [1]

[5] "Deep" water could perhaps be considered to have a depth greater than 50 m.

[6] Bulder et al. [3], Fulton et al. [4], Tong [11]

[7] Niedzwecki and Moe [9], Moe and Niedzwecki [8], Moe [7]

installation in shallow water depth. She has found that a truss tower uses significantly less steel, and therefore could provide a cost savings, depending upon the manufacturing techniques that are used, since the truss requires more assembly and welding.

Paul Thomassen is a postdoc, who recently began in the department; he will be researching the analysis of support structures. One of his topics is to address the ways in which loads from the rotor can be represented statistically, for purposes of fatigue design of support structures, without running time-series analyses of the dynamic response of the entire turbine.

Karl Merz (the author) is a PhD candidate; he is researching potential designs of deep-water support structures, including a reinforced concrete floating platform of a spar-buoy configuration, and a cable-stayed tower.[8] Taking a long-term view, he would like to find an optimal configuration from the perspective of minimizing the ratio of input to output energy; that is, the ratio of energy used to create the materials and build, install, operate, and decommission the turbine, to the energy delivered by the turbine over its operational lifetime.

2.2 Control Systems

Frederik Sandquist is a PhD candidate; he is researching the degree to which rotor loads can be reduced by implementing individual pitch control of each rotor blade; he has found that a significant reduction in loads can be achieved. He has written software that simulates turbine structural and control system dynamics, in which different variables can be measured and fed into the control system.

2.3 Aerodynamics

Simon-Philippe Breton earned his doctoral degree at the department in June, 2008; his thesis[9] focused primarily on the analysis of NREL Phase VI (unsteady aerodynamics experiment) model wind turbine data, comparing strain measurements and finite element calculations with aerodynamic pressure measurements in order to obtain a reliable estimate of physical behaviour. He also used the data to evaluate the accuracy of various published methods of accounting for rotational effects on airfoil lift and drag forces, also known as "stall delay", using a prescribed-wake vortex analysis. He found that the method of Lindenburg[10]

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[8] I have only recently begun the design process, and therefore have no results to present at the time of this writing.

[9] Breton [2]

[10] Lindenburg [5]

correlated best with NREL data, although none of the methods, including Lindenburg, predicted loading along the blade consistently over a range of operating conditions.

BIBLIOGRAPHY

[1] Berntsen, T.O., et al. ; "Vindkraft offshore – industrielle muligheter for Norge" ; Ministry of Petroleum and Energy, 2008 (Norwegian)

[2] Breton, S.P. ; *Study of the stall delay phenomenon and of wind turbine blade dynamics using numerical approaches and NREL's wind tunnel tests*; doctoral thesis, NTNU, 2008:171

[3] Bulder, B.H., et al.; "Feasibility study of floating wind farms in shallow offshore sites"; Wind Engineering 27 (2003) 405-418

[4] Fulton, G.R., et al.; "Semi-submersible platform and anchor foundation systems for wind turbine support"; NREL/SR-500-40282, 2007

[5] Lindenburg, C.; *Investigation into rotor blade aerodynamics*; ECN-C—03-025, Petten, Netherlands, 2003

[6] Moe, G. ; "Vindturbiner – Hvorfor, og hva i Norge?" ; presentation, 2008 (Norwegian)

[7] Moe, G.; "What is the optimum size of a wind turbine"; Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering, Paper OMAE 2007-29035, San Diego, USA

[8] Moe, G.; Niedzwecki, J.; "Frequency of maxima of non-narrow banded stochastic processes", Applied Ocean Research, Volume 27, Issue 6, pp. 265-272

[9] Niedzwecki, J.; Moe, G.; "Investigation of a caternary riser undergoing VIV"; Proceedings of the Third International Conference on Fluid Structure Interaction, La Corona, Spain, 2005

[10] Tester, J.W., et al.; *Sustainable Energy -- Choosing Among Options*; MIT Press, 2005

[11] Tong, K.C.; "Technical and economic aspects of a floating offshore wind farm"; Journal of Wind Engineering and Industrial Aerodynamics 74-76 (1998) 399-410