Final Technical Report
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IEA Wind Annex 21

Dynamic Models of Wind Farms for Power System Studies

iea wind

IEA WIND Annex XXI

Final Technical Report

Dynamic models of wind farms for power system studies

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ABSTRACT

This report summarizes the results of the International Energy Agency working group IEA Wind Annex 21. The report includes sections on wind farm modelling, measurements, benchmark test procedures and example test results.

The section on wind farm modelling gives an introductory to the main issues and a summary of models developed by the Annex participants. References are given for more extensive coverage.

The section on measurements provides for an overview of the measurement data that have been collected and shared amongst the Annex partners.

The sections on the benchmark test procedures and test results provide for a significant technical contribution. The report is the first to present a systematic comparison of wind generation models against measurements. The report concludes that results give a clear indication of accuracy and usability of the models tested, and pin-point the need for both model development and testing

The individual works of the Annex participants are summarized in Appendices to this report.

PREFACE

This report has been prepared as a joint effort by the participants of the international working group Annex 21 that was initiated April 2002 by the Executive Committee of the International Energy Agency implementing agreement for co-operation in the research, development, and deployment of wind energy systems.

The overall objective of the Annex was to assist the planning and design of wind farms by facilitating a coordinated effort to develop wind farm models suitable for use in combination with software packages for simulation and analysis of power system stability. The effort comprises the following immediate objectives and activities:

1. Establish an international forum for exchanging knowledge and experience within the field of wind farm modelling for power system studies
2. Develop, describe, and validate wind farm models.
   (The wind farm models are expected to be developed by individual participants of the task, whereas the description and validation will be coordinated by the task, which helps provide state-of-the-art models and pinpoint key issues for further development.)
3. Set-up and operate a common database for benchmark testing of wind turbine and wind farm models as an aid for securing good-quality models.

The Annex included participants from nine countries (Sweden, Finland, Norway, Portugal, Netherlands, Denmark, USA, UK and Ireland) as listed below:

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The Annex has been carried out on a cost- and task-shared basis. The participants have contributed with financial support to the Operating Agent (SINTEF Energy Research, represented by John Olav G Tande) for coordination of the Annex and have carried out activities, supplied information, and joined meetings as required to meet the objectives of the Annex.

EXECUTIVE SUMMARY

INTRODUCTION

Large wind power installations may have a significant impact on the power system stability that must be assessed prior to installation, and for this, accurate dynamic wind generation models are critical. Hence, model validation is a key issue and taken up by Task XXI under the IEA Wind R&D agreement. The task has since start-up in 2002 developed a systematic approach for model benchmark testing. The rationale for the proposed benchmark testing is that currently dynamic wind generation models are being applied for assessing grid connection of large wind farms, though model accuracy are not always known. This at best leads to uncertainty in the market, and at worst to an erroneous design jeopardising power system stability. The challenge is twofold. Firstly, the technology in modern wind farms is fairly complex, and their dynamic behaviour may differ significantly depending on the wind turbine type and manufacturer specific technical solutions. Thus, it is not trivial to develop accurate wind generation models. Secondly, model validation must be transparent and adequate for providing confidence. In this respect, the Task has contributed by describing a benchmark procedure, and applied this for testing numerical wind generation models.

MEANS AND OBJECTIVES

The overall objective is to assist the planning and design of wind farms by facilitating a coordinated effort to develop wind farm models suitable for use in combination with software packages for simulation and analysis of power system stability. The effort comprises the following immediate objectives and activities:

- Establish an international forum for exchanging knowledge and experience within the field of wind farm modelling for power system studies
- Develop, describe, and validate wind farm models.
  (The wind farm models are developed by the individual participants of the task, whereas the description and validation are coordinated by the task, which helps provide state-of-the-art models and pinpoint key issues for further development.)
- Set-up and operate a common database for benchmark testing of wind turbine and wind farm models as an aid for securing good-quality models.

The Annex has been carried out on a cost- and task-shared basis with participants from nine countries (Denmark, Finland, Ireland, the Netherlands, Norway, Sweden, the United Kingdom, the United States and Portugal) with research institutes and universities carrying out work to develop and test wind farm models, as well as doing grid studies in cooperation with wind turbine manufacturers and electric utilities.

The participants have contributed with financial support to the Operating Agent (SINTEF Energy Research, represented by John Olav G Tande) for coordination of the Annex and have carried out activities, supplied information, and joined meetings as required to meet the objectives of the Annex. Cooperation within the task has been through sharing measurement data, model descriptions, and discussions at meetings. A total of eight task meetings have been arranged.

RESULTS

Model developments are ongoing among participants, including both fixed- and variable-speed technologies and by using various software tools (Matlab/Simulink, PSS/E, SIMPOW, DIgSILENT and EMTDC).

An internet "e-room" has been established for sharing documents and measurement data among the participants of the Task. The database part of the e-room contains measurements from fixed and variable speed wind turbines. The participants may download these data and continue using the measured data after completion of the Task, but shall not distribute the data (except obviously they remind in full right to distribute their own data as they like).

A method for benchmark testing of models has been established by the Task, and selected models developed by the Task participants have been tested. The tests include both validation against measurements and model-to-model comparisons, and they consider dynamic operation during normal, fault-free conditions and response to voltage dips. See Fig 1 and 2 for examples of measurements and simulations of response to voltage dips. In total some 14 models have been tested, including models of both fixed speed and variable speed wind turbines.

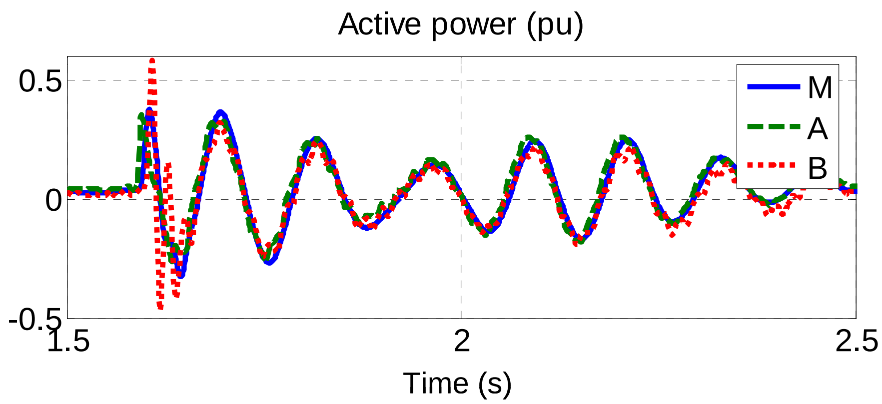

Figure 1: Time-series plot of measured and simulated active power output from a fixed speed, stall controlled wind turbine with squirrel-cage induction generator during a voltage dip on the grid. M is measurement, A and B are simulations.

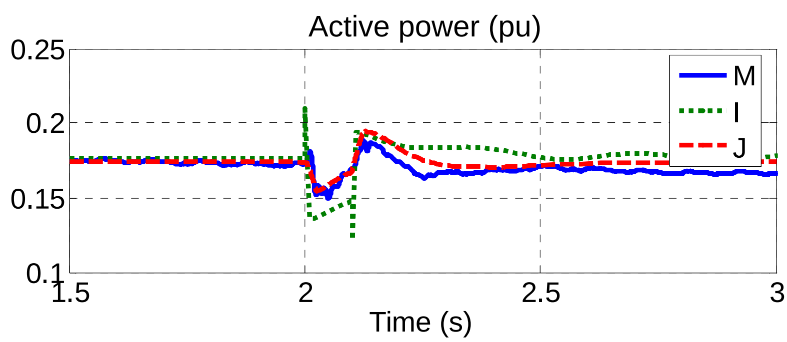

Figure 2: Time-series plot of measured and simulated active power output from a variable speed wind turbine with doubly-fed induction generator during a voltage dip on the grid. M is measurement, I and J are simulations.

A topic of high interest is the ability of wind turbines to ride through temporary grid faults, hence, contributing to grid stability. Detailed numerical models may be used to assess such abilities, but these models must be validated against measurements to provide confidence. A proposal emerging as a spin-off from Task XXI is to update IEC 61400-21 (Measurements and assessment of power quality characteristics of grid connected wind turbines, ed. 1, 2001) to specify requirements for such testing. This work is now about to conclude with the circulation of IEC 61400-21, ed. 2 as a Final International Draft Standard by spring 2008. Hence, in the future, wind turbine manufacturers may refer to standard test certificates for demonstrating performance under grid transients, and also these same test certificates may be used for validating dynamic models of wind farms for power system studies.

The work of Task XXI including description of the benchmark test procedure and presentation of test results provide for a significant technical contribution. The Task is the first to present a systematic comparison of wind generation models against measurements. The test results give a clear indication of accuracy and usability of the models tested, and pin-point the need for both model development and testing.

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1 INTRODUCTION

1.1 Background

Large wind power installations may have a significant impact on the power system stability that must be assessed prior to installation. Such assessment is commonly conducted using commercial available software packages for simulation and analysis of power systems. These packages normally facilitate a set of well-developed models of conventional components such as fossil fuel fired power stations and transmission network components, whereas models of wind turbines or wind farms represent new features with in many cases unknown accuracy. This at best leads to uncertainty in the market, and at worst to an erroneous design jeopardising the power system stability.

The challenge is twofold. Firstly, the technology in modern wind farms is fairly complex, and their dynamic behaviour may differ significantly depending on the wind turbine type and manufacturer specific technical solutions. Secondly, model validation must be transparent and adequate for providing confidence. Thus, for a coordinated effort aiming to enhance progress a working group (Annex 21) with participants from nine countries was initiated April 2002 under the International Energy Agency implementing agreement for co-operation in the research, development, and deployment of wind energy systems (IEA Wind).

1.2 Scope

This report presents the results of works by the Annex, i.e. including an overview of dynamic wind farm models (section 2), collected measurements from wind power installations (section 3), procedure for benchmark testing of models (section 4), and example benchmark test results (section 5).

The overview section on dynamic wind farm models gives brief model descriptions only, whereas references are included for more detailed descriptions. The models considered are for various software tools (PSS/E, SIMPOW, DIgSILENT, Matlab/Simulink, etc) and for various wind farm technologies (fixed speed wind turbines, variable speed wind turbines with doubly feed induction generator, direct drive wind turbines with multi-pole synchronous generator, etc).

The section on measurements provides for an overview of the measurement data that have been collected and shared amongst the Annex partners.

Model validation is a key issue for creating confidence. The use of invalidated models in power system studies may result in dramatically erroneous conclusions, i.e. grossly over- or under-predicting the impact of a wind farm on power system stability. The Annex consequently suggests benchmark procedures for validating model performance, i.e. validation against measurements and model-to-model comparisons. The procedure for this is explained together with example test results. The procedure considers both operation at normal fault free conditions and response to voltage dips.

The current situation with on the one hand very varying level of confidence and knowledge about wind farm grid interaction modelling, and on the other hand ever larger wind farm projects being planned, the importance and relevance of the Annex works is highlighted. A key issue is thus dissemination of Annex results, i.e. being the goal of this report.

The sections on the benchmark test procedures and test results provide for a significant technical contribution. The report is the first to present a systematic comparison of wind generation models against measurements. The report concludes that results give a clear indication of accuracy and usability of the models tested, and pin-point the need for both model development and testing

Symbols, data conversion formulas and wind turbine data used in this report are listed in Appendix I – IV, and the individual works of the Annex participants are summarized in Appendix V-XIII. Selected Annex 21 papers are reprinted in Appendix XIV.

2 WIND FARM MODELLING

Accurate simulation of wind farms relies on detailed modelling of the applied wind turbine technology, e.g. the dynamic behaviour of a fixed-speed wind turbine may differ significantly from that of a variable-speed wind turbine. Figure 1 shows the main wind turbine types, but there will also be manufacturer specific variations, in particular related to control system solutions. Aggregated models may be applied, i.e. letting one wind turbine model representing multiple turbines in a wind farm, but the impact of the spatial distribution and the internal wind farm grid must be reflected.

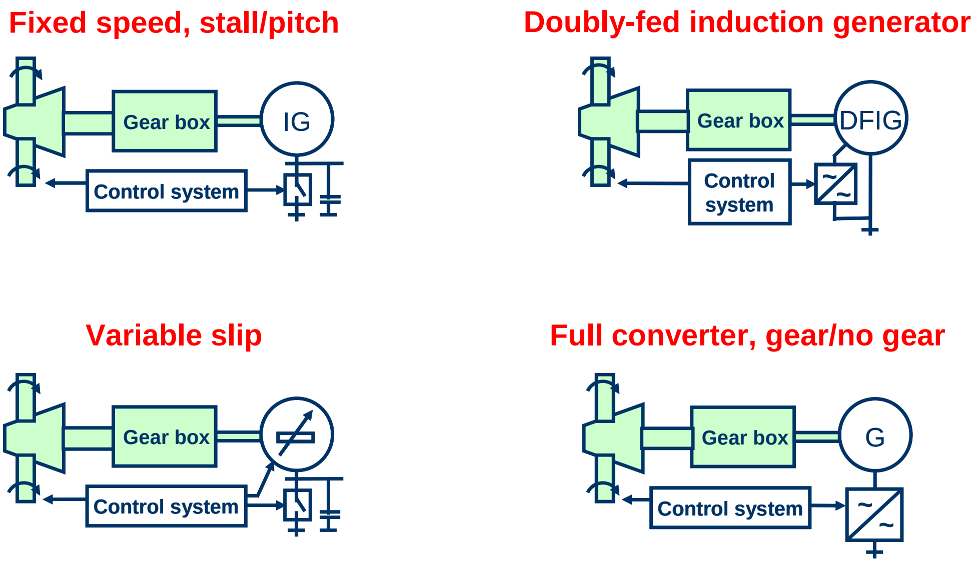


Figure 1: Main types of wind turbine technologies.

2.1 Wind turbine model building blocks

A detailed wind turbine model may include the following components:

- wind speed
- turbine aerodynamics
- mechanical drive-train
- generator
- capacitors or frequency converter
- control system
- other issues (relay protection, tower swings, etc)

A fair wind speed and turbine aerodynamic representation is required for simulating the aerodynamic torque fluctuations. One challenge in this relation is to include the effect of wind speed variations over the turbine area, i.e. an effect that may cause enhanced 3p power fluctuations from wind turbines. This can be done using wind field simulations and detailed blade profile data or by application of the following relation:

$$T_t = 0.5 \rho A u_t^3 C_p(\lambda, \beta) \omega_t^{-1} \quad (1)$$

Here, T_t is aerodynamic torque, ρ is the air density, A is the swept turbine area, u_t is the weighted average wind speed over the three rotating turbine blades, $C_p(\lambda,\beta)$ is the turbine aerodynamic efficiency as a function of tip-speed ratio (λ) and blade pitch angle (β), and ω_t is the rotational speed of the turbine. The weighted average wind speed over the three rotating turbine blades, u_t, can be determined from wind field simulations or by filtering of a single point wind speed time-series.

The mechanical drive train is commonly approximated by a two mass model, i.e. the turbine and generator inertia with a shaft and an ideal gearbox between them. Applying pu values with reference to the generator the two mass model is given by:

$$\frac{d\omega_t}{dt} = \frac{\omega_b}{2H_t}\left(T_t - d_m\left(\omega_t - \omega_g\right) - k\theta_t\right) \tag{2}$$

$$\frac{d\omega_g}{dt} = \frac{\omega_b}{2H_g}\left(d_m\left(\omega_t - \omega_g\right) + k\theta_t - T_g\right) \tag{3}$$

Here, $d\omega_t/dt$ is the time derivate of the turbine rotational speed, ω_b is the base angular frequency, H_t is the turbine inertia, d_m is the mutual damping, ω_g is the rotational speed of the generator, k is the shaft stiffness, θ_t is the shaft twist, $d\omega_g/dt$ is the time derivate of the generator rotational speed, and H_g is generator inertia.

The generator models applied may be of varying complexity. Third order models are commonly used in tools for simulation of large power systems, whereas more detailed models may be used in tools for analyses of smaller systems. These detailed models may include stator dynamics (fifth order model), and further particulars such as full three-phase description.

The capacitors applied for reactive compensation of fixed speed wind turbines are commonly modelled as one or more shunt impedances.

In tools for simulation of large power systems the frequency converter is commonly described as an ideal component, i.e. neglecting losses and the switching dynamics. In more detailed studies these effects may be included, e.g. for assessment of harmonics.

The control system model for a fixed speed wind turbine is commonly split into two independent blocks, i.e. one for the pitching of the blades and one for switching the capacitors. The control system of variable speed wind turbines may be fairly complex, including speed control for optimising the production, but also producing a smooth output power, and further special regulation may be implemented for low-voltage ride-through and other off-normal grid situations.

Other issues such as e.g. relay protection and tower swings may be included in some models. The relevance of including such issues depends on the scope of the analysis.

2.2 Wind farm models

Wind farm models may be built to various level of detail ranging from a one-to-one modelling approach to full aggregation. The one-to-one approach is more computer demanding and in many cases not practical, hence aggregated wind farm models are often applied in power system studies. The aggregation is however not trivial, i.e. considering that a wind farm may consist of hundreds of wind turbines distributed over a large area with different impedance of line feeder from one turbine with respect to the others, different wind speeds at each turbine and different voltage drops on each bus. Aggregated models must therefore be applied with care. Possibly a cluster-by-cluster aggregation may be a fair compromise between one-to-one modelling and full aggregation.

2.3 IEA Wind Annex 21 models

The models developed by the Annex participants and benchmark tested as reported in Section 5 are briefly described below. References are included for detailed descriptions. For an overview of all wind turbine and wind farm models developed by the partners, see paper on Annex 21 status from EWEC'04 [22] (reprint in Appendix XIV).

Fixed-speed wind turbine with squirrel-cage induction generator and stall control:

A. Model A (Chalmers, voltage dip) is built in Matlab/Simulink with a third-order generator model and a two-mass model of the mechanical drive train. Chalmers work on modelling of fixed speed wind turbines are described in the licentiate thesis "Wind Turbine Models for Power System Stability Studies" by Abram Perdana, [27], hereunder Chapter 4 "Validation of Fixed Speed Wind Turbine Models". See also [29] and Appendix V.
B. Model B (University College Dublin, voltage dip) is built in Simulink using a fifth order representation of the squirrel cage induction machine model. The machine model is coupled with a shaft model which is represented in Simulink as two rotational masses coupled by a spring and damper. See also Appendix XII.
C. Model C (VTT, voltage dip) is implemented in PSCAD/EMTDC by using the standard component library components. The generator is modeled by the Squirrel-cage Induction Machine component, the mechanical drive-train with the Torsional Shaft Model component (multi-mass) and the capacitor bank with Capacitor components.
D. Model D (Risø, voltage dip) is built in DIgSILENT using an RMS (phasor) simulation which applies a standard third-order model of the induction generator, together with a user-built two-mass model of the mechanical drive train. See [31] for model description. Appendix IX gives an extensive list of references to Risø publications on modelling.
E. Model E (INETI, voltage dip) is part of a wind farm simulation tool (InPark) programmed in Fortran. It applies a fifth-order model of the induction generator, the representation of the structural oscillations first mode, and a two-mass model of the mechanical drive train. The model is described in Appendix VII and in detail in [23] and [39]. [39] includes simulation results of normal operation.
F. Model F (NREL, voltage dip and normal operation) is part of a renewable energy power systems modular simulator (RPMSim). It applies a fifth-order model of the induction generator and a two-mass model of the mechanical drive train. The model is described in Appendix VIII and in detail in [32].
G. Model G (ECN and TU Delft, voltage dip and normal operation) is built in Matlab/Simulink with a fifth-order generator model and a two-mass spring and damper model of the mechanical drive train. The model is described in Appendix VI and in detail in [2], [33] and [34].

H. Model H (SINTEF, voltage dip and normal operation) is built in SIMPOW using a standard third-order generator model, a two-mass model of the mechanical drive train, and user-built models of aerodynamics and wind speed. See Appendix X for further description of the model.

Variable-speed wind turbine with doubly fed induction generator and pitch control:

I. Model I (SINTEF, voltage dip) is implemented in PSS/E. It uses a user-built third-order generator model and a two-mass representation of the turbine and generator inertias. See Appendix X for further description of the model.
J. Model J (SINTEF, voltage dip) is implemented in SIMPOW. It uses a user-built third-order generator model and a two-mass representation of the turbine and generator inertias. See Appendix X for further description of the model.
K. Model K (Chalmers, voltage dip) is a full-order model built in Matlab. Chalmers works on DFIG modelling are described in the PhD thesis “Analysis, Modelling and Control of Doubly-Fed Induction Generator for Wind Turbines” by Andreas Peterson, [26], hereunder Chapter 6 “Evaluation of Doubly-Fed Induction Generator Systems”. See also [30].
L. Model L (Chalmers, voltage dip) is a third-order model built in Matlab, though not “classical” as this model L includes stator dynamics and neglects rotor electrical dynamics. Reference to further description is as for model K.
M. Model M (VTT, voltage dip) is implemented in PSCAD. It consists of the converter bridge and its controls, wound rotor generator component and single mass representation of the drive train. The measured voltage is used as input to the simulation of the voltage dip.
N. Model N (ECN, voltage dip and normal operation) is built in Matlab/Simulink with a fifth-order generator model and a two-mass spring and damper model of the mechanical drive train. The model is described in Appendix VI and in detail in [2], [33] and [35].

3 MEASUREMENT DATABASE

An important activity of the Annex was the establishment of a database with technical descriptions, simulations and measurement data from wind turbines and wind farms. The data contained in the database is listed below.

- WT500 (Denmark); 500 kW fixed speed, stall controlled wind turbine, measurement during normal operation.
- Alsvik (Sweden); 4x180 kW wind farm (fixed speed, stall controlled), measurement during normal operation and measurement + simulated response to voltage dip.
- Olos (Finland); 5x600 kW wind farm (fixed speed, stall controlled), measurements during normal operation and response to voltage dip.
- Azores (Portugal); 4x100 + 1x150 kW wind farm (fixed speed, stall controlled), measurements during normal operation.
- DFIG850 (Sweden); 850 kW DFIG wind turbine, measurement during normal operation and response to voltage dip.
- SimWT (Denmark); simulated response of fixed speed wind turbine on voltage dip (simulations in EMTDC and DIgSILENT).
- Smøla (Norway); 20x2 MW wind farm (fixed speed, active stall Bonus wind turbines), measurements during normal operation and response to voltage dip.
- CART (USA); 600 kW full converter wind turbine measurements during normal operation and response to voltage dip.

The present dataset provides a fair basis for testing the benchmark procedures, but should ideally include more data and measurements to constitute a better basis for model validation. It seems that relevant data are very often restricted and for that reason cannot be shared within the Annex.

The data in the database are for the use of the Annex partners only.

4 BENCHMARK TEST PROCEDURE

The benchmark test procedures suggested by IEA Wind R&D Annex 21 consider operation during normal conditions and wind turbine response to a voltage dip. In both cases the test data include three-phase measurements of instantaneous voltages and currents at the wind turbine or wind farm terminals. The benchmark test procedure includes transforming these measurements to RMS fundamental positive sequence values of voltage, active power and reactive power for comparison with simulation results. The benchmark test may include both validation against measurements and model-to-model comparisons.

4.1 Dynamic operation during normal conditions

This test is for validating model capability to simulate wind turbine or wind farm characteristic power fluctuations during normal grid conditions. The test is outlined below.

Input:
- Wind speed time series (and optionally voltage time series)

Output:
- Time series plot of active power output, reactive power, and voltage (optionally)
- Power spectral density of active power output
- Short-term flicker emission
- Optionally plots of reactive power versus voltage and reactive power versus active power

4.2 Response to voltage dip

This test is for validating model capability to simulate wind turbine or wind farm response to a voltage dip. The test is outlined below.

Input:
- Voltage time series and constant aerodynamic torque (or optionally wind speed time series). The voltage time series must include information of about both voltage amplitude and phase angle, i.e. in the form of a positive sequence voltage phasor (complex) or three phase instantaneous values.

Output:
- Time series plot of active and reactive power output
- Time series of voltage at wind turbine terminals

4.3 Transformation of measurement data

Assuming a perfectly balanced three-phase system it requires a minimum of data processing to calculate instantaneous values of P and Q and RMS values of U and I:

$$U = \sqrt{u_1^2 + u_2^2 + u_3^2} \tag{1}$$

$$I = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2}{3}} \tag{2}$$

$$P = u_1 i_1 + u_2 i_2 + u_3 i_3 \quad (3)$$

$$Q = -\frac{(u_2 - u_3)i_1 + (u_3 - u_1)i_2 + (u_1 - u_2)i_3}{\sqrt{3}} \quad (4)$$

The recommendation of the Annex is however *not* to use the above eqs. (1) - (4), but rather to calculate the fundamental positive sequence voltage and current phasors, and from these calculate the active and reactive power for comparison with simulation results. The fundamental voltage and current phasors are determined using the complex Fourier transformation (shown here for the voltage in phase *a* only):

$$U_{a1} = \frac{2}{T} \int_{t-T}^{T} u_a(t) e^{-j\omega_1 t} dt \quad (5)$$

Here, U_{a1} is the fundamental voltage phasor of phase *a*, *T* is the fundamental period time and ω_1 is the fundamental frequency in radians. The positive sequence values are given by (shown here for voltage only):

$$U_+ = (U_{a1} + U_{b1} e^{j2\pi/3} + U_{c1} e^{-j2\pi/3})/3 \quad (6)$$

Here, U_+ is the fundamental positive sequence voltage phasor, U_{b1} is the fundamental voltage phasor of phase *b* and U_{c1} is the fundamental voltage phasor of phase *c*. Calculation of the active and reactive power is now straight forward:

$$S_+ = \sqrt{3} U_+ I_+^* = P_+ + jQ_+ \quad (7)$$

Here, S_+ is the complex apparent power, the subscript plus-sign ($_+$) indicates that the value is based on the fundamental positive sequence, and the superscript asterisk-sign (*) indicates the complex conjugate. Active and reactive power calculated according to eq. (10) is hereafter in this paper denoted positive sequence active and reactive power.

The reason for using the fundamental positive sequence values is twofold. Firstly, perfectly balanced conditions can not generally be assumed, and events of voltage dips are often unbalanced. Secondly, most power system simulator models are phasor-type models, meaning that the electrical variables (voltages and currents) are represented as positive sequence values. This is also discussed in [21]. The use and calculation of the positive sequence values are described in detail in [20].

5 EXAMPLE TEST RESULTS

This section presents example benchmark test results comparing simulation results against measurements of wind turbine normal operation and response to voltage dips. Measurement data from “Alsvik” and “DFIG850” are used, see also Section 3.

The Alsvik cases consider a 180 kW fixed-speed wind turbine with squirrel-cage induction generator and stall control. The assumed wind turbine data are listed in Appendix III.

The DFIG850 cases consider an 850 kW variable-speed wind turbine with doubly fed induction generator and pitch control. The assumed wind turbine data are listed in Appendix IV.

The measurements are compared with simulation results from application of various numerical models developed by the Annex partners, see also Section 2.3.

5.1 Normal operation of fixed-speed wind turbine

In this section example test results are presented comparing measurements and simulations of a 180 kW fixed speed, stall controlled wind turbine during normal operation.

The time-series plot of active and reactive power output, Figure 2 and Figure 3, shows fair agreement between the measurement and simulation. The time lag between the two is because the wind speed is measured at some distance up-stream of the wind turbine.

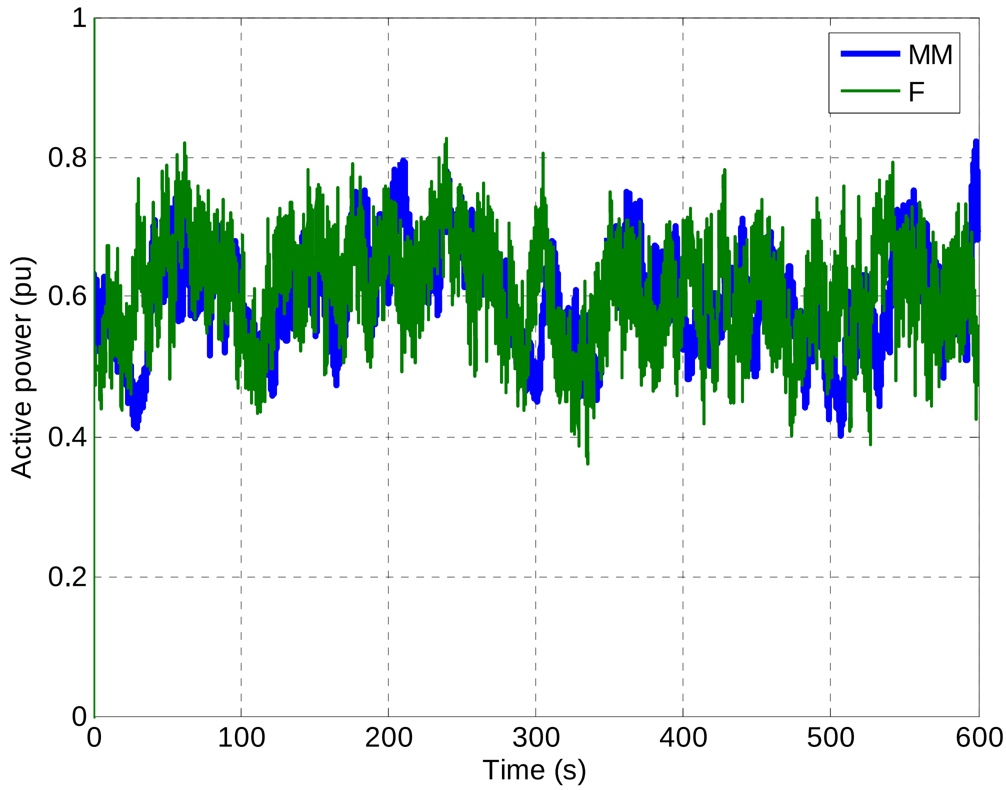


Figure 2: Measured and simulated active power output from fixed speed, stall controlled wind turbine.

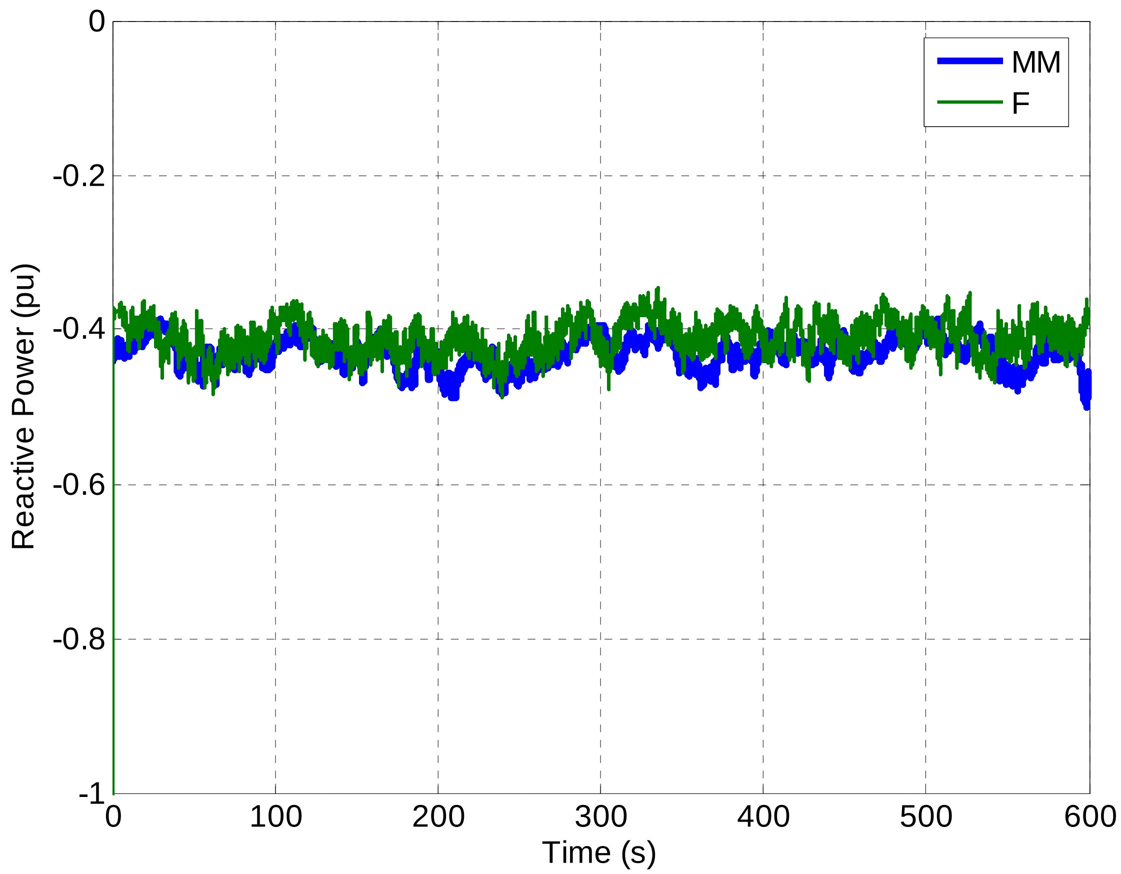


Figure 3: Measured and simulated reactive power output from fixed speed, stall controlled wind turbine.

The time-series plots of Figure 2 and Figure 3 are mainly for illustration. A better basis for comparison between measurements and simulations are obtained by plotting the power spectral density of the signal, shown in Figure 4 for models F, G and H.

The power spectral density (PSD) plot of active power output, Figure 4, indicate significant power fluctuations at 0.7 Hz (1p = turbine rotational frequency, fluctuation probably due to unbalanced blades), 1.1 Hz (fluctuation probably due to tower swing) and 2.1 Hz (3p, fluctuation due to variations in wind speed over the rotor area). Model F appears to underestimate these lower frequencies characteristic fluctuations, and introduces a significant fluctuation at about 10 Hz. Model G approximates well the fluctuations at multiples of 3p, but does not include the unbalanced blades (0.7 Hz) and tower swing (1.1 Hz) fluctuations. Model H matches well the 3p fluctuation and the tower swing (the model includes a first order representation of the tower mode), though slightly underestimates the higher frequency fluctuations.

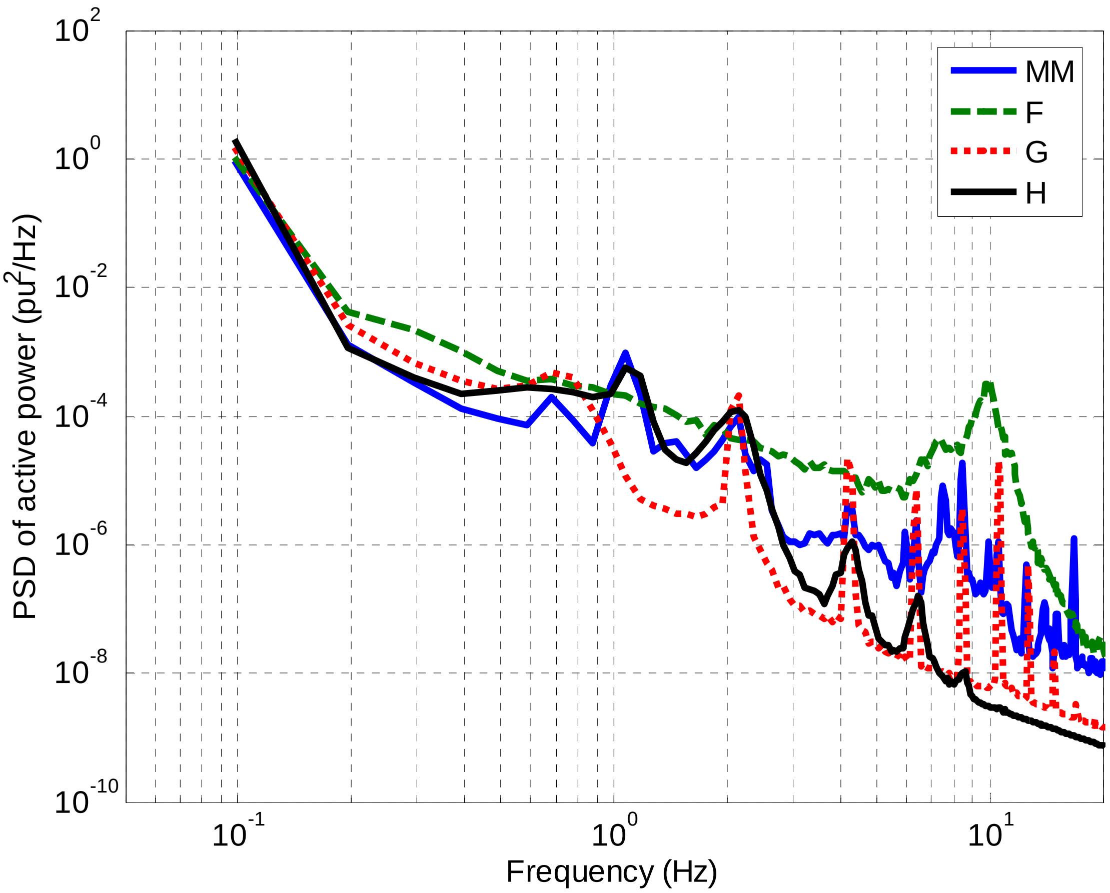


Figure 4: Power spectral density (PSD) of measured and simulated active power output from fixed speed, stall controlled wind turbine.

5.2 Voltage dip response of fixed-speed wind turbine

The measurements of three-phase instantaneous voltages and currents at the wind turbine terminals were recorded with a sample rate of 256 Hz during the voltage dip. The sample rate should preferably be higher, say at least 1 kHz, so for the purpose of this report, the data are numerically re-sampled to 1250 Hz. The measured instantaneous data are shown in Figure 5.

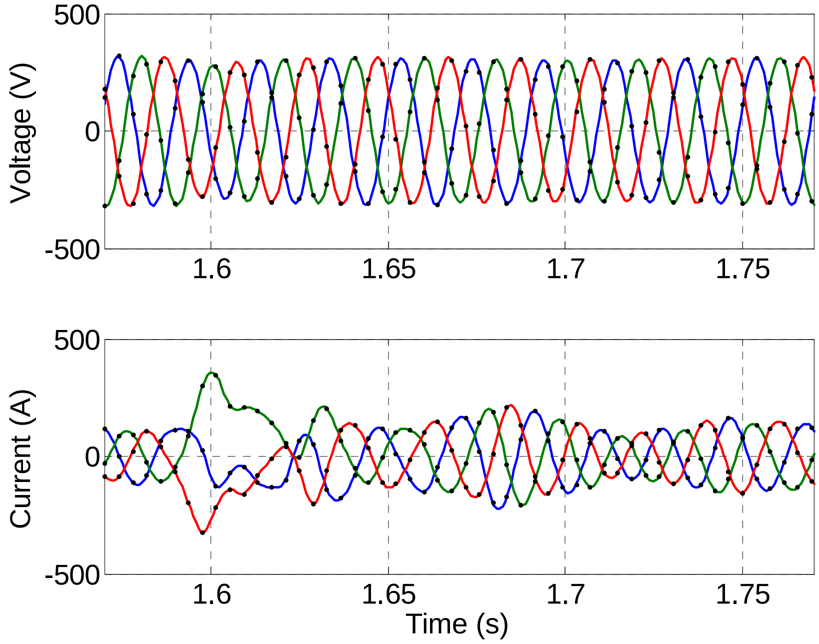


Figure 5: Measured instantaneous three-phase voltages and currents at wind turbine terminals during a grid fault causing a voltage dip. The original data are indicated by dots.

Analysis of the measurement data reveals some unbalance just when the dip occurs, but apart from this, no significant difference is observed between positive sequence values and those calculated using eqs. (3)- (4), see Figure 6. The positive sequence voltage is shown in Figure 7. It seen that the voltage dip gives a phase angle deviation that may also be interpreted as a frequency variation. This variation explains the measured rather high fluctuation in active power from the wind turbine that would otherwise not be expected from the small voltage dip.

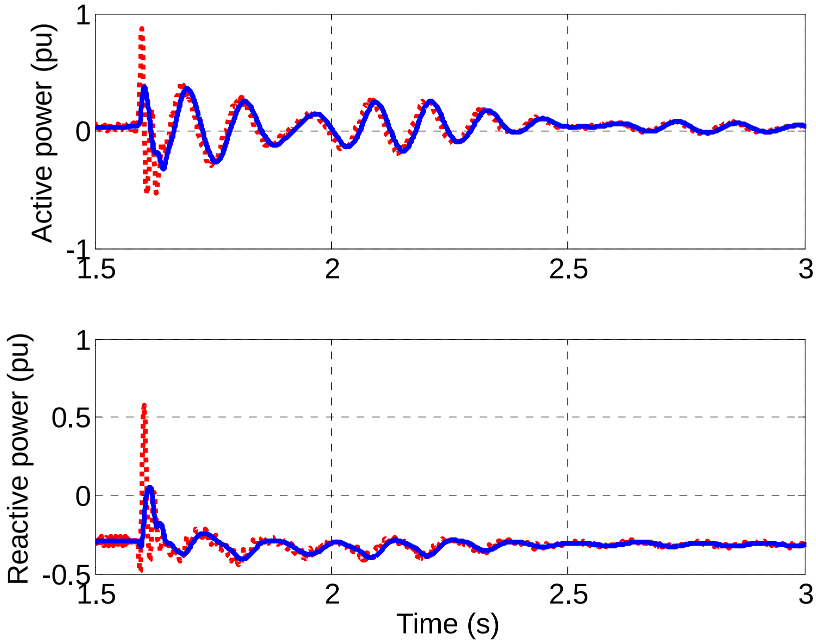


Figure 6: Instantaneous (dotted line) and positive sequence (solid line) values of measured active and reactive power at wind turbine terminals during a voltage dip.

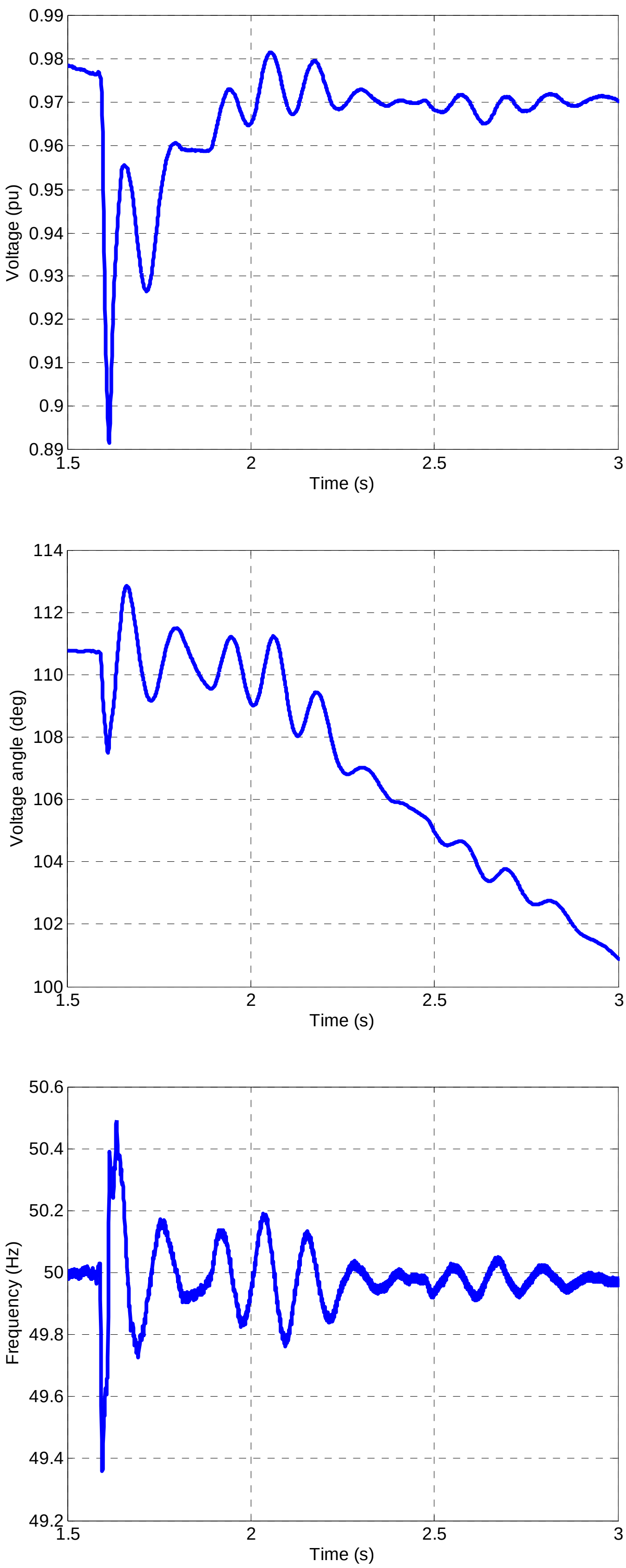


Figure 7: Voltage positive sequence amplitude (upper graph) and angle (middle graph). The lower graph shows the voltage phase angle deviation interpreted as a frequency variation.

The measurements are compared with simulation results of models developed by the Annex partners, see Section 2.3. The models (A-H) apply the measured voltage dip (amplitude and phase or instantaneous values) as input.

Comparing the measured and simulated response in active and reactive power (Figure 8 and Figure 9), the models provide for varying results. This is in part due to differences in model type, but also due to variations in model input data. In particular it is noted that the wind turbine data as given in the Appendix are uncertain, and slightly different parameters have been applied in some models:

- The stated generator inertia seems very small (H_g = 0.12 s), and in models A-D and H a higher inertia was applied (H_g = 0.24 s) providing for fluctuations in active power with a frequency closely matching the measurements. The reasoning is that in a two mass representation, the generator inertia should be lumped with the inertia of the high speed shaft.
- The shunt capacitor is rated Q_c = 60 kvar, but it is not know if it was connected at the time of the voltage dip. Using Q_c = 16 kvar (models A-C and H) provides for a better match between simulations and measurements.
- The presence of the high frequency components shown in the simulation by model F is probably caused an underdamped mechanical ringing in the flexible shaft.

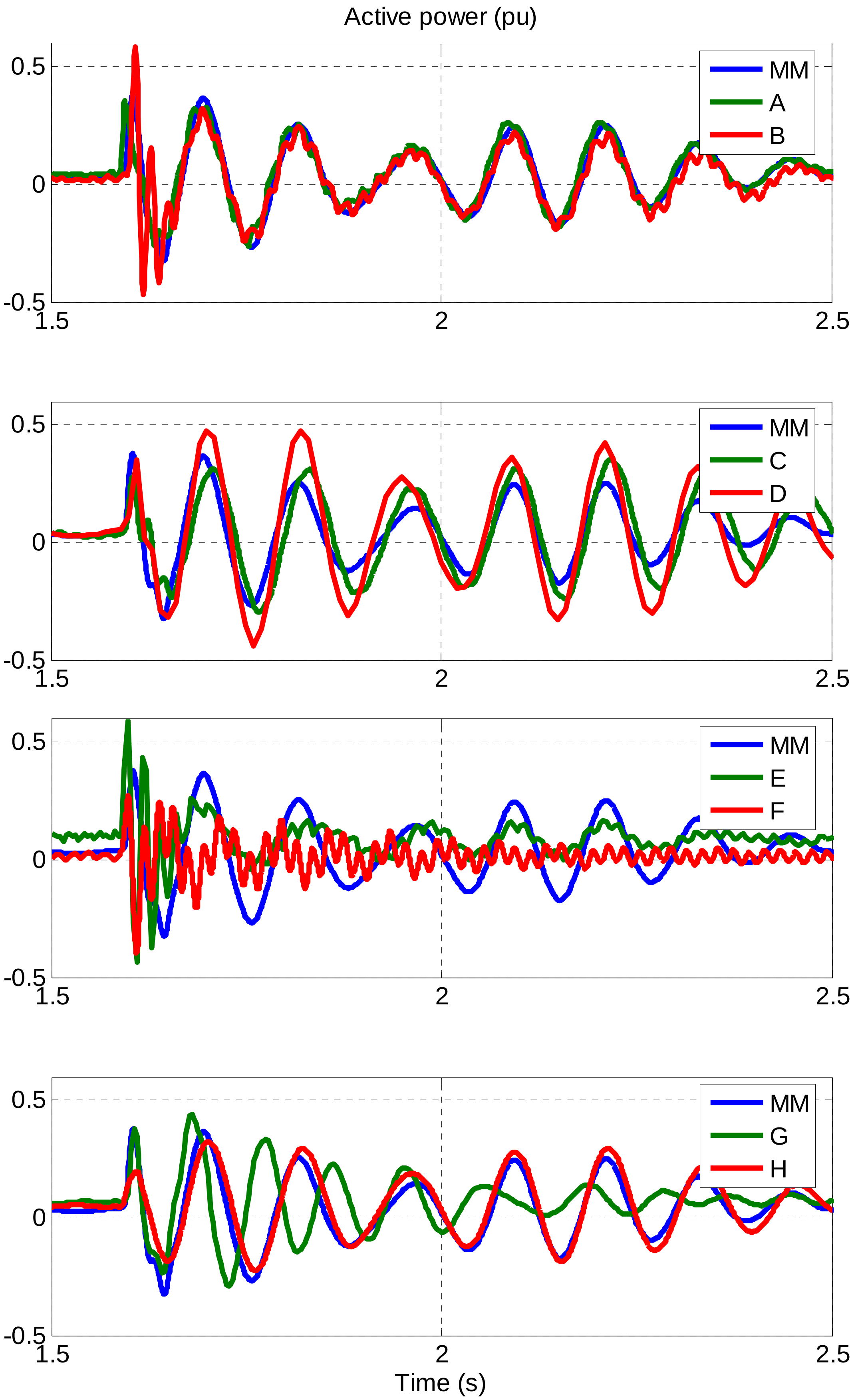


Figure 8: Measured (MM) and simulated (A-H) positive sequence active power at wind turbine terminals during a voltage dip.

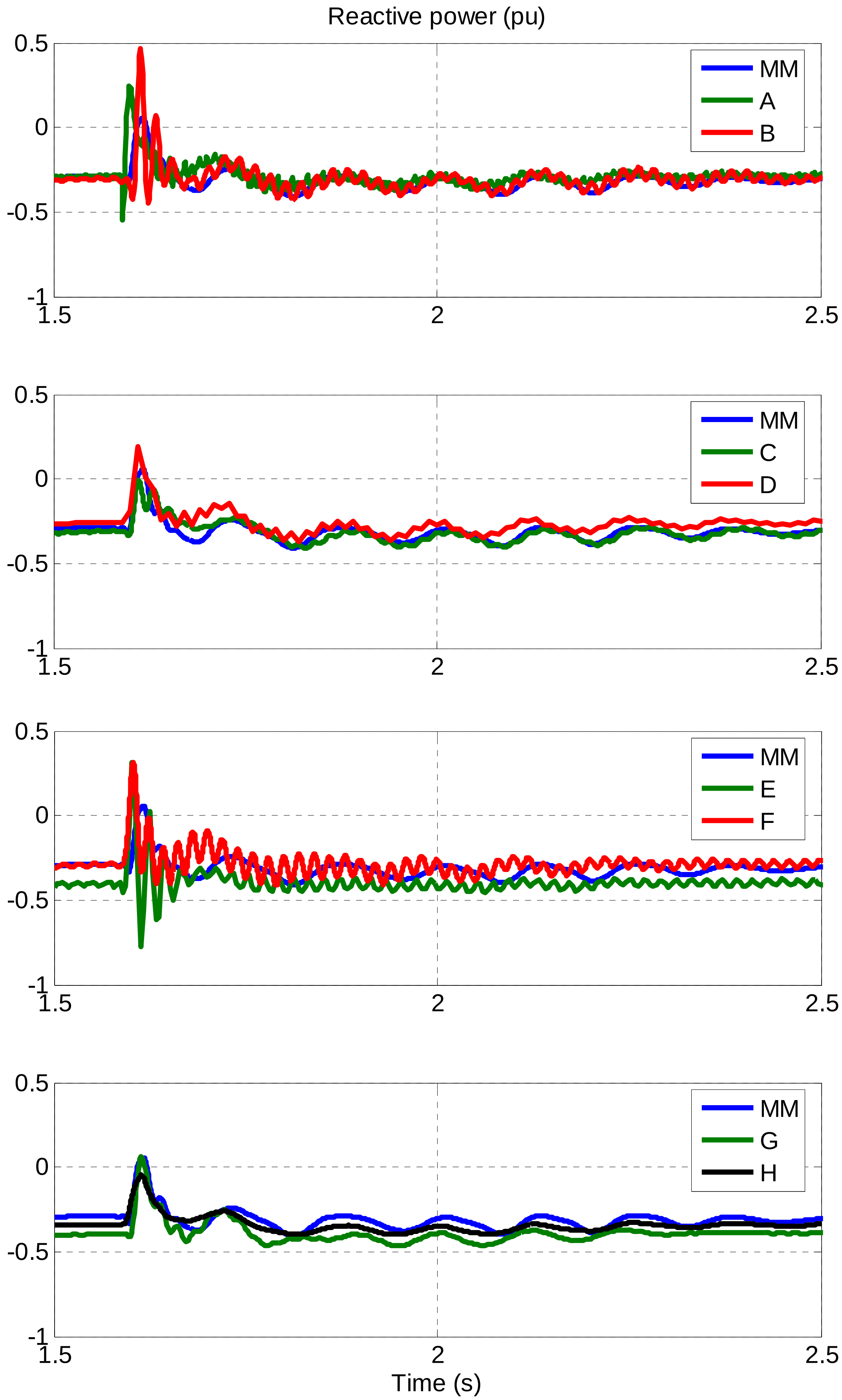


Figure 9: Measured (MM) and simulated (A-H) positive sequence reactive power at wind turbine terminals during a voltage dip.

5.3 Normal operation of variable-speed wind turbine

In this section example test results are presented comparing measurements and simulations during normal operation of an 850 kW variable-speed wind turbine with doubly fed induction generator and pitch control.

Figure 10 shows measured active power for three different cases of operation, i.e. at high, medium and low wind speed operation.

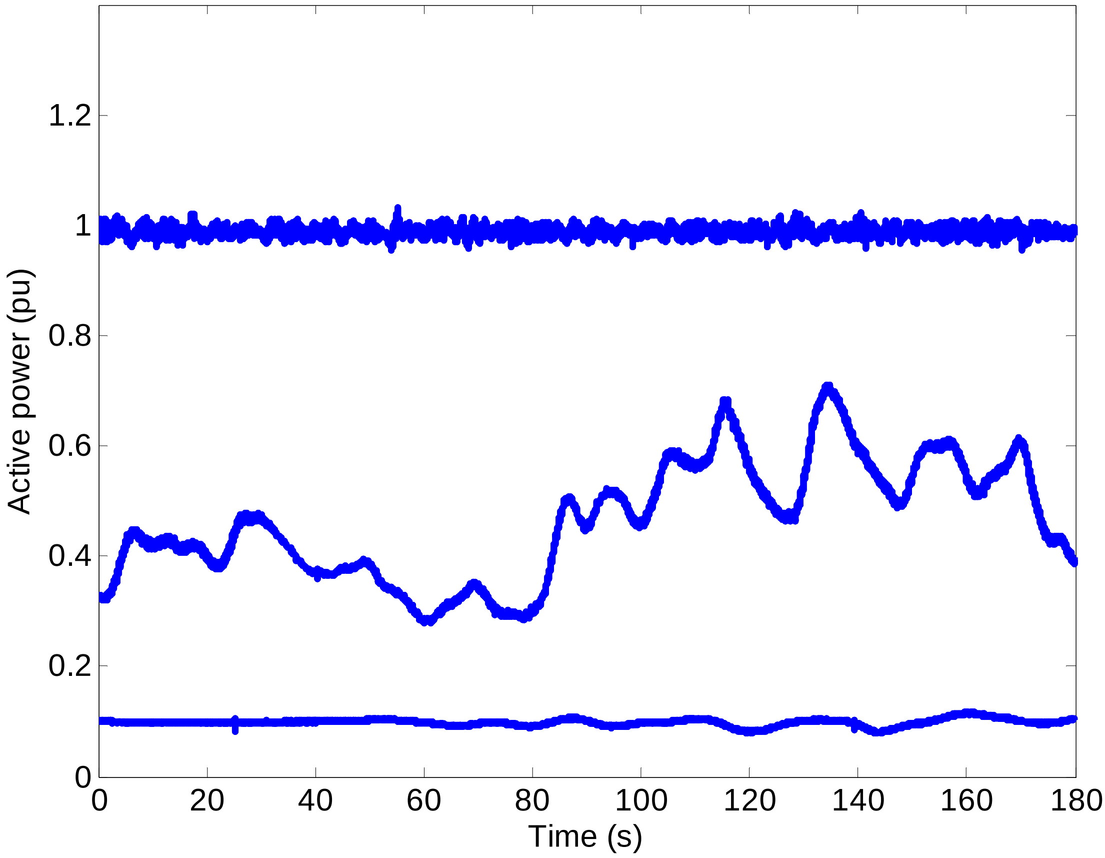


Figure 10: Measured active power output from DFIG wind turbine at high, medium and low wind speed.

The simulations (model N) are in this case prepared not using the given parameters in the Appendix, but a slightly different set of representative parameters. The model N does not use the measured wind speed time series as input but the average measured wind speed. The wind speed model creates a statistically correct rotor average wind speed including the sampling effect of the blades.

The power spectral density (PSD) plot of active power output, Figure 11, shows as the time-series plots that the power fluctuations are well damped. Model N appears to represent this quite well.

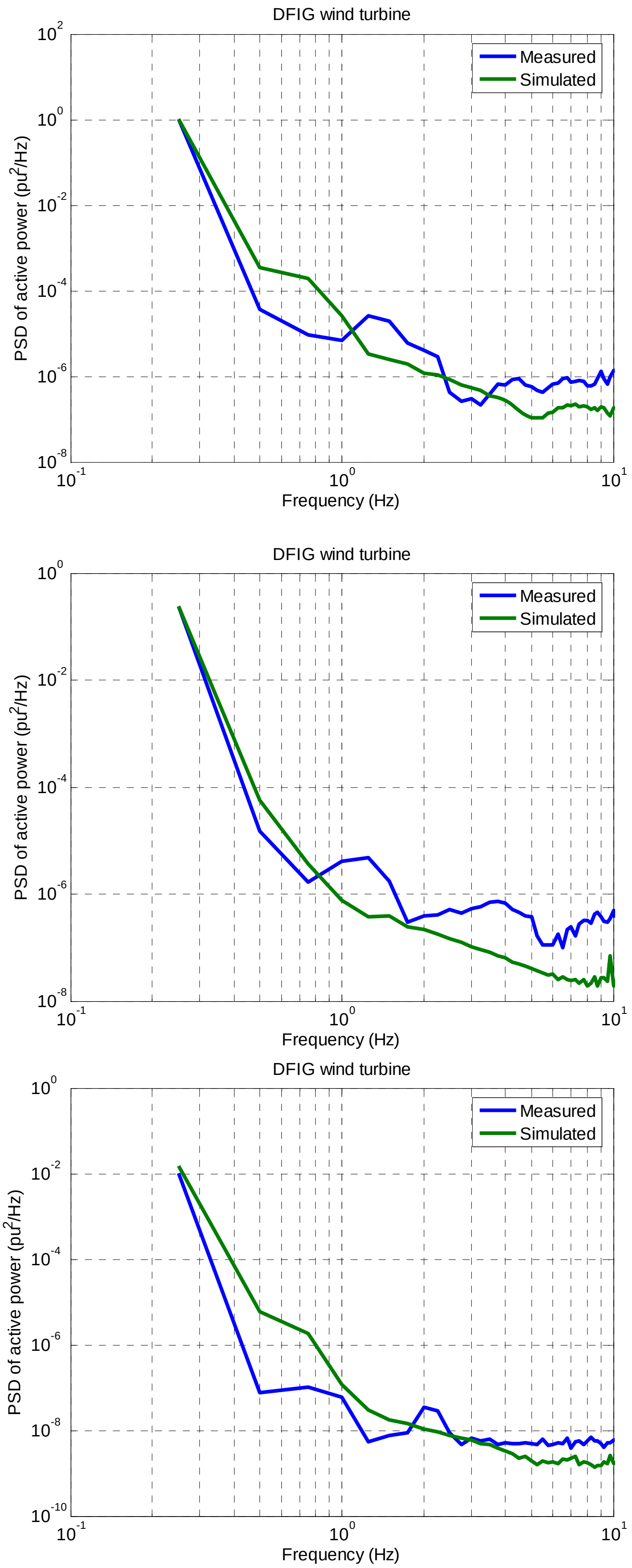


Figure 11: Power spectral density (PSD) of measured and simulated active power output from DFIG wind turbine. The upper graph is for operation at rated power, the middle is at middle power and the lower graph is low power.

5.4 Voltage dip response of variable-speed wind turbine

This test considers an 850 kW variable-speed wind turbine with doubly fed induction generator and pitch control. The assumed wind turbine data are listed in the Appendix. Measurements of three-phase instantaneous voltages and currents at the wind turbine terminals are recorded with a sample rate of 2048 Hz during a voltage dip. The measured instantaneous data are shown in Figure 12.

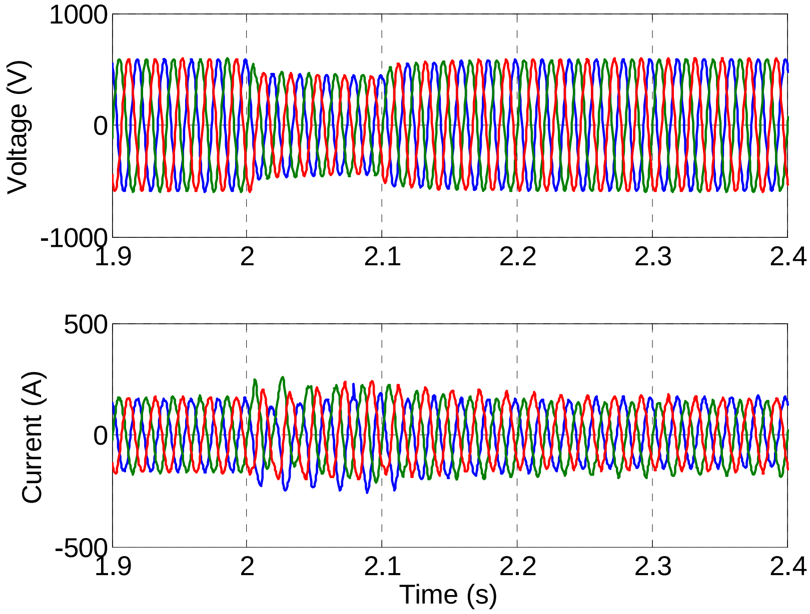


Figure 12: Measured instantaneous three-phase voltages and currents at wind turbine terminals during a grid fault causing a voltage dip.

Analysis of the measurement data reveals that the dip is unbalanced and a significant difference is observed between positive sequence values and those calculated using eqs. (3)- (4), see Figure 13. The positive sequence voltage is shown in Figure 14.

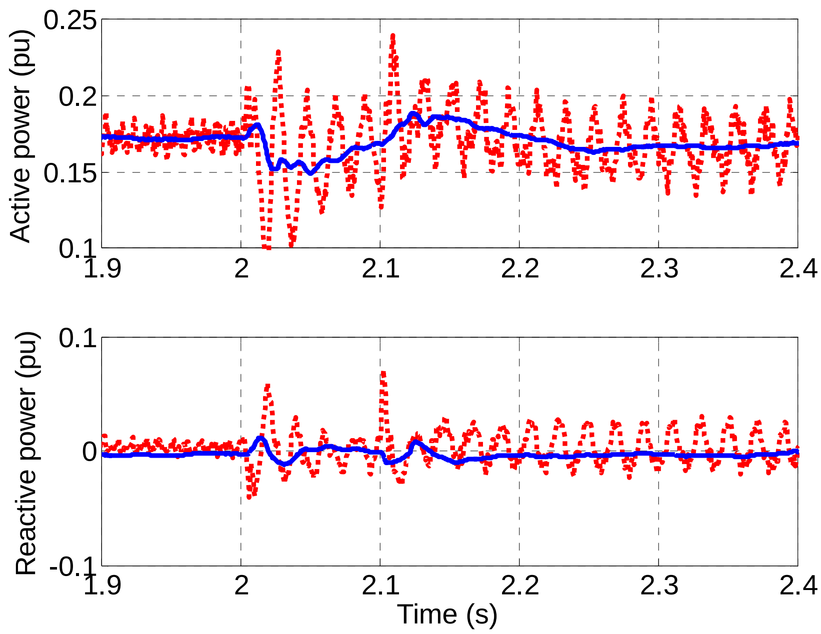


Figure 13: Instantaneous (dotted line) and positive sequence (solid line) values of measured active and reactive power at wind turbine terminals during a voltage dip.

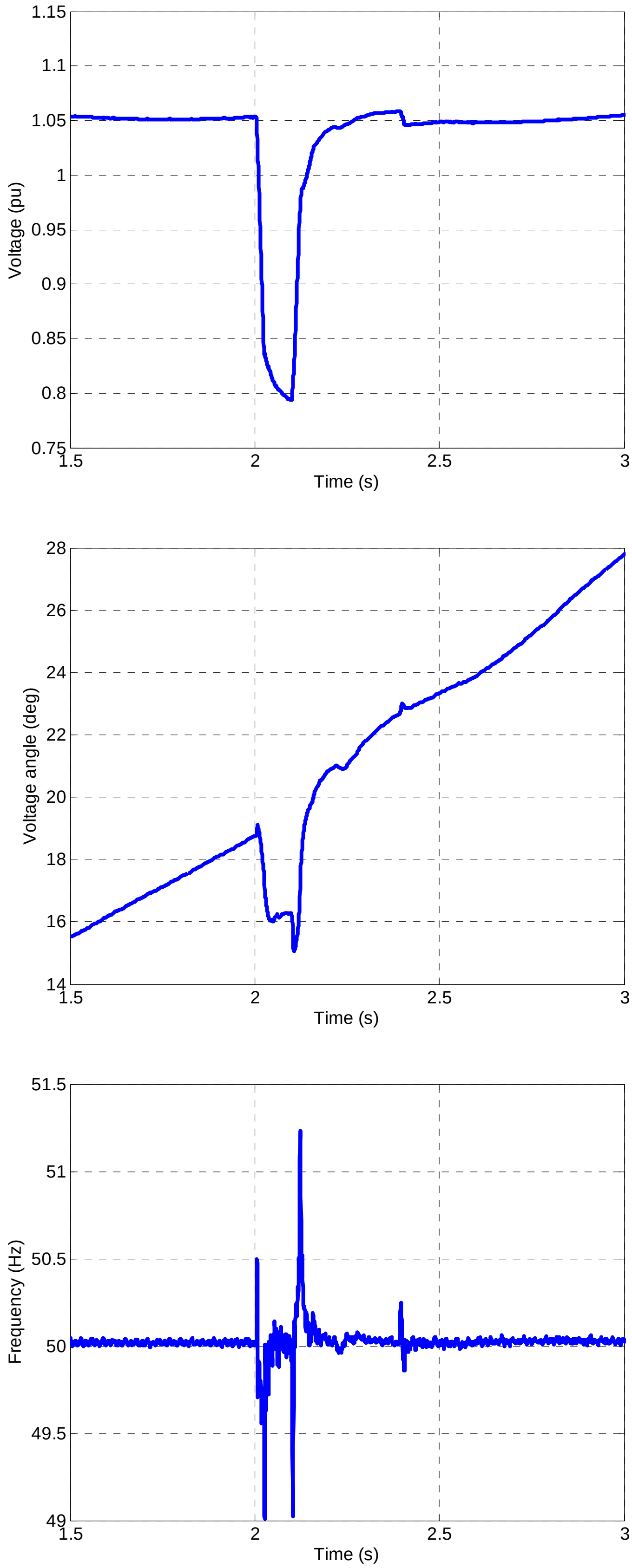


Figure 14: Voltage positive sequence amplitude (upper graph) and angle (middle graph). The lower graph shows the voltage phase angle deviation interpreted as a frequency variation.

The measurements are compared with simulation results of the developed by the Annex partners, see Section 2.3. The models (I-N) apply the measured voltage dip (amplitude and phase or instantaneous values) as input.

Comparing the measured and simulated response in active and reactive power (Figure 15 and Figure 16), the models provide for fair, but varying results. The variations are in part due to differences in model type, but also due to variations in model input data. It is noted that the applied wind turbine data as given in the Appendix are uncertain. This also goes for the applied control structure; the models (I - N) are of generic nature reflecting main characteristics of DFIG wind turbines and are not a one-to-one representation of manufacturer specific details:

- Models I, J and M gives a fairly smooth response matching very well the measured positive sequence active power.
- Model I and J are third-order models neglecting stator dynamics, i.e. positive sequence phasor models and therefore not giving any 50 Hz fluctuations in the output.
- Model M is a fifth order model that could be expected to give 50 Hz fluctuations, but because of the implemented control of the power electronic converter these are well damped in model M. The spikes in reactive power by model M is also due to the implemented control system.
- Models K, L and N all include stator dynamics and a control of the power electronic converter that give 50 Hz fluctuations resembling that of the measured instantaneous active power fluctuations.
- Models K and L give a good match, whereas the fluctuations are overestimated by model N. The reason for the overestimation of model N is likely due to the applied control of the power electronic converter and that the parameters of the power electronic converter were not known or tuned to fit the measurements.

An important observation is that the response on the voltage dip is governed by the applied control of the power electronic converter. The strong 50 Hz component present in the measurement is not saying that all DFIG turbines have this characteristic, i.e. in large modern DFIG turbines this 50 Hz component is expected to be well damped. The possibility of this is demonstrated here by simulation (model M). It is suggested in [21] that third (or higher) order generator models may not be well suited for simulation of a DFIG wind turbine response to a voltage dip in power system simulation tools like PSS/E. The reasoning is that to obtain reasonable voltage dip simulation results (as shown here), such high order models requires integration time steps in the order of 0.1 ms, and hence makes the simulation slow in tools like PSS/E (that operates at fixed time-steps) and less suitable for practical use. A possible improvement may thus be to assume instant rotor current control, and then only consider the main limitations in converter voltage and current. This would allow for using a steady-state generator model and larger integration time steps.

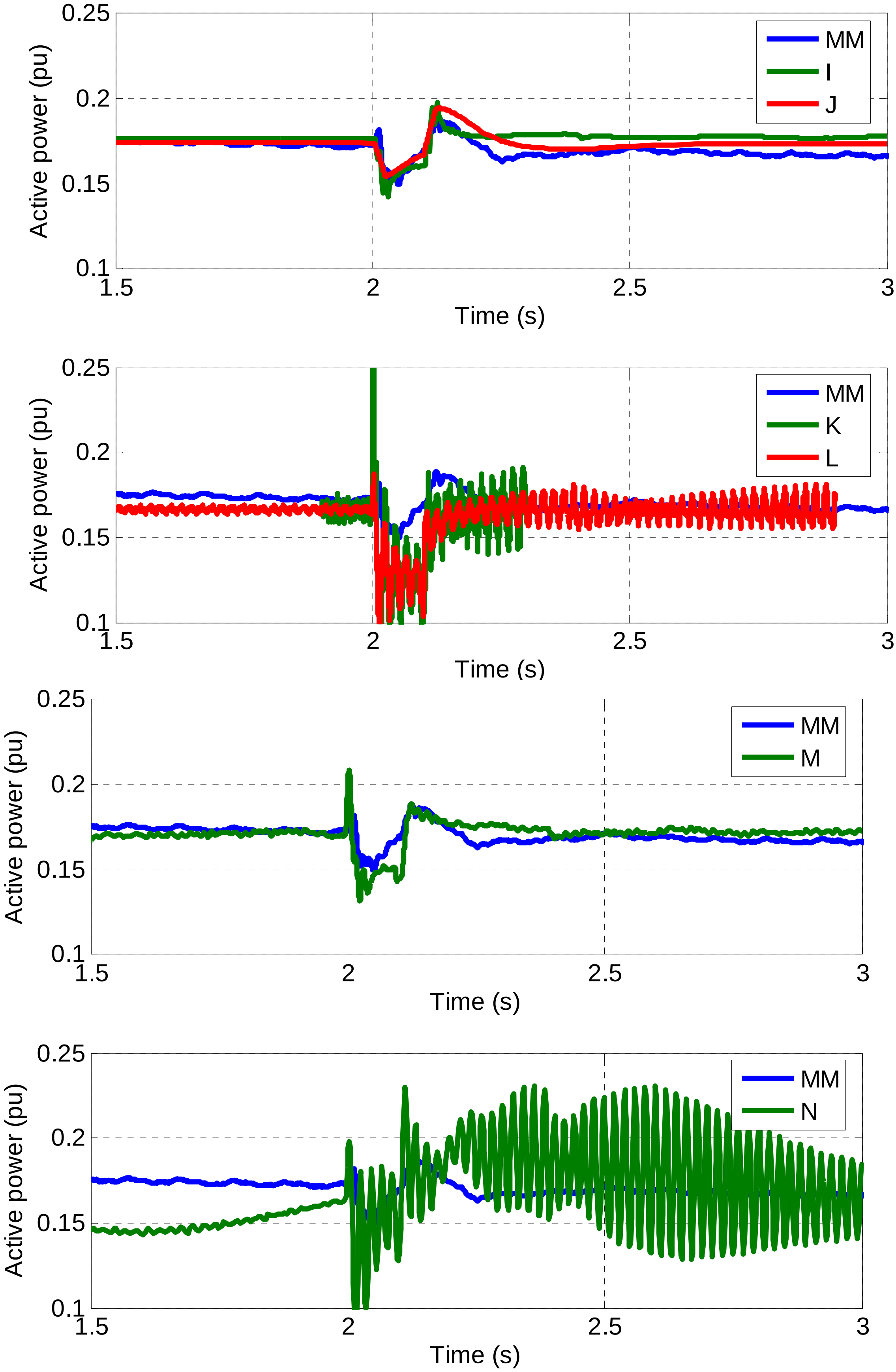


Figure 15: Measured (MM) and simulated (I-N) positive sequence values of active power at wind turbine terminals during a voltage dip.

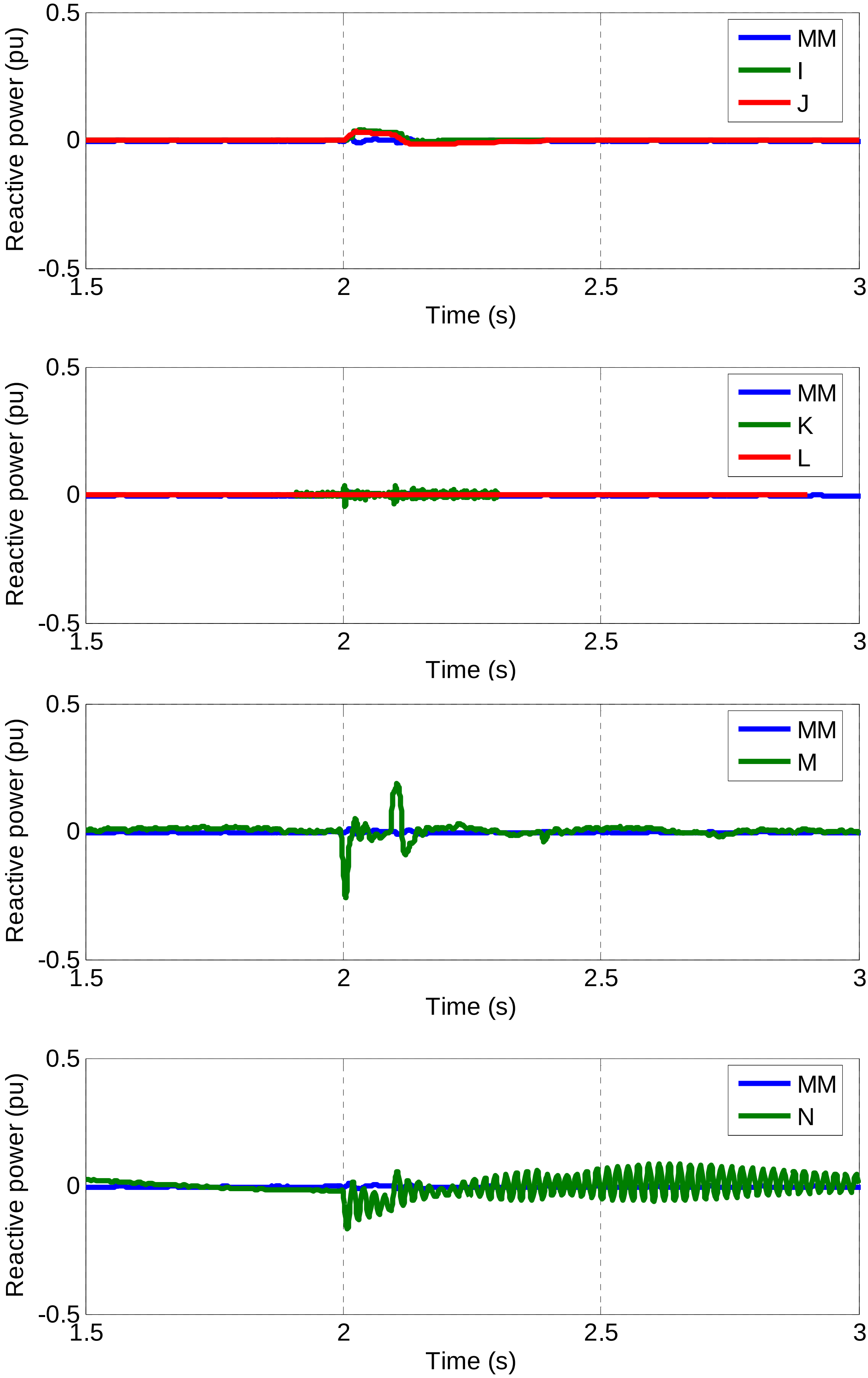


Figure 16: Measured (MM) and simulated (I - N) positive sequence values of reactive power at wind turbine terminals during a voltage dip.

6 CONCLUSION

This report has presented results from studies conducted by the IEA Annex 21 on ‘Dynamic models of wind turbines for power system studies’. The systematic approach developed by the Annex for model benchmark testing was described and examples were shown which compare wind generation models against measurements of wind turbine response to voltage dips. The test results were illustrated for both fixed-speed wind turbines with squirrel-cage induction generator and variable-speed wind turbines based on doubly-fed induction generators. In order to compare measured results with those from a phasor/RMS type simulation, especially in the case of voltage dips, the Annex recommends transforming the measured voltage and current to positive sequence values and from these deducting the active and reactive power.

The benchmark test results showed for the majority of the models a good agreement with the measurements. This demonstrates generally satisfactory model performance, but also that benchmark testing is important for providing confidence. It can be summarised that the results provided a clear indication of accuracy and applicability of the models tested and identified the necessity for both model development and testing.

Model validation is a key issue for creating confidence. The use of invalidated models in power system studies may result in dramatically erroneous conclusions, i.e. grossly over- or under-predicting the impact of a wind farm on power system stability. The Annex consequently suggests benchmark procedures for validating model performance, i.e. validation against measurements and model-to-model comparisons.

REFERENCES

[1] T. Thiringer, A. Petersson, T. Petru, "Grid Disturbance response of Wind Turbines Equipped with Induction generator and Doubly-Fed Induction generator" IEEE PES annual Meeting, Toronto, Canada, 2003, July 14-17.

[2] JTG Pierik, J Morren, EJ Wiggelinkhuizen, SWH de Haan, TG van Engelen, J Bozelie; Electrical and control aspects of offshore wind farms, Volume 1: Dynamic models of wind farms, ECN-C-04-050, ECN / TU Delft June 2004.

[3] JTG Pierik, J Morren, EJ Wiggelinkhuizen, SWH de Haan, TG van Engelen, J Bozelie; Electrical and control aspects of offshore wind farms, Volume 2: Offshore wind farm case studies, ECN-C-04-050, ECN / TU Delft June 2004.

[4] Estanqueiro, A. , WIRING Project Final Report (JOR3-CT98-0245) INETI Contribution, Part A: *Theoretical Basis of INETI's INPark Wind Park and Local Grid Models*. Sept, 2002. pp. 57.

[5] Estanqueiro, A. , WIRING Project Final Report (JOR3-CT98-0245) INETI Contrib., Part B*: Application of the Models*,. Sept, 2002. pp.39.

[6] Jesus, J. ; Estanqueiro, A.; Saraiva, J.; Castro, R. , Modelling Machine Interaction In A Wind Park With Regard To Stability And Regulation, PO-MISTRAL NATO SFS PROGRAMME III, Final Report, Febr. 2001, pp 108.

[7] Castro, R and J. Jesus. An Aggregated Wind Park Model, 13th Power System Computation Conference- PSCC'99; Trondheim. Jun –99

[8] E. Muljadi, C.P. Butterfield, "Dynamic Model for Wind Farm Power Systems," Global Wind Power Conference 2004 in Chicago, IL, March 29-April 1, 2004

[9] E. Muljadi, C.P. Butterfield, "Dynamic Simulation of a Wind Farm with Variable Speed Wind Turbines," Transactions of the ASME, Vol. 125, November 2003, Special Issue on Wind Energy, Journal of Solar Energy Engineering, pp. 410-417

[10] Sørensen, P.; Hansen, A.D.; Christensen, P.; Mieritz, M.; Bech, J.; Bak-Jensen, B.; Nielsen, H., Simulation and verification of transient events in large wind power installations. Risø-R-1331(EN) (2003) 80 p.

[11] Sørensen, P.; Hansen, A.D.; Janosi, L.; Bech, J.; Bak-Jensen, B., Simulation of interaction between wind farm and power system. Risø-R-1281(EN) (2001) 65 p.

[12] Tande, JOG; Grid Integration of Wind Farms, Wind Energ. 2003; 6:281–295

[13] Ian Norheim, K Uhlen, JOG Tande, T Toftevaag, MT Pálsson; Doubly Fed Induction Generator Model for Power System Simulation Tools, Nordic Wind Power Conference, 1-2 Marcg, 2004, Chalmers University of Technology

[14] Palsson MT, Toftevaag T, Uhlen K, Tande JOG. Large-scale wind power integration and voltage stability limits in regional networks. Proceedings of IEEE-PES Summer Meeting, 2002; 2: 762–769.

[15] A Mullane; Advanced control of wind energy conversion systems, Thesis (Ph.D.) NUI, 2003 at Department of Electrical and Electronic Engineering, UCC.

[16] Anaya-Lara, O., Cartwright, P., Ekanayake, J. B., "Electrical Stability of Large Wind Farms – Grid Connections and Modelling," Proceedings of the Global Windpower Conference 2004, Chicago, Illinois, USA, March 2004.

[17] Anaya-Lara, O., Wu, X., Cartwright, P., Ekanayake, J. B., Jenkins, N., "Performance of

Doubly Fed Induction Generator (DFIG) During Network Faults," Paper accepted for publication in the IEE Proceedings on Generation, Transmission and Distribution, April 2004.

[18] Ekanayake, J. B., Holdsworth, L., Jenkins, N., "Comparison of 5th order and 3rd order machine models for Doubly Fed Induction Generator (DFIG) Wind Turbines", Proceedings Electric Power System Research, Vol. 67, 2003, pp. 207-215.

[19] Uski, S., Lemström, B., Kiviluoma, J., Rissanen, S. and Antikainen P. Adjoint wind turbine modeling with ADAMS, Simulink and PSCAD/EMTDC. Nordic wind power conference – NWPC'04, 1-2 March 2004 at Chalmers University of Technology, Gothenburg, Sweden.

[20] Jouko Niiranen, "About the active and reactive power measurements in unsymmetrical voltage dip ride through testing", In proceedings of Nordic Wind Power Conference, 22-23 May, 2006, Espoo, Finland, available at http://nwpc.vtt.fi/program_nwpc_files/frame.htm

[21] Kjetil Uhlen, Ian Norheim, John Olav Giæver Tande "Wind farm measurements and modelling", In proceedings of European Wind Energy Conference (EWEC) Athens, Greece, 27 February - 2 March 2006, available at http://www.ewec2006proceedings.info/

[22] Tande JO, E Muljadi, O Carlson, J Pierik, A Estanqueiro, P Sørensen, M O'Malley, A Mullane, O Anaya-Lara, B Lemstrom (2004) "Dynamic models of wind farms for power system studies – status by IEA Wind R&D Annex 21", In proceedings of European Wind Energy Conference (EWEC), 22-25 November 2004, London, UK.

[23] Ana I. Estanqueiro, J. Lameira (2006) "IEA Task 21 Final Report, INETI Contribution, Part A: Theoretical Basis of INETI's INPark Wind Park and Local Grid Models", Departamento de Energias Renováveis, INETI, December 2006.

[24] Martins, M. "Voltage Stability Issues Related to Implementation of Large WindFarms", Göteborg, Sweden, Chalmers University of Technology, June 2006.

[25] Petru T. "Modeling of Wind Turbines for Power System Studies", Göteborg, Sweden, Chalmers University of Technology, School of Electrical Engineering, Technical Report No. 449,ISSN 1651-498X, ISBN 91-7291-306-1, June 2003.

[26] Petersson A. "Analysis, Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines", Göteborg, Sweden, Chalmers University of Technology, School of Electrical Engineering, ISBN 91-7291-600-1, 2005.

[27] Perdana A. "Wind Turbine Models for Power System Stability Studies", Göteborg, Sweden, Chalmers University of Technology, October 2006.

[28] Ullah, N. R. "Grid Reinforcing Wind Generation", Göteborg, Sweden, Chalmers University of Technology, May 2006.

[29] Martins M., Perdana A., Ledesma P., Agneholm E., Carlson O., "Validation of fix speed wind turbine dynamics with measured data", Renewable Energy, Volume 32, Issue 8, July 2007, Pages 1301-1316.

[30] Petersson A., Thiringer T., Harnefors L., Petru T., "Modeling and Experimental Verification of Grid Interaction of a DFIG Wind Turbine", IEEE Transactions on Energy Conversion, Vol. 20, No. 4, Dec. 2005 pp. 878 – 886.

[31] Hansen, A.D.; Jauch, C.; Sørensen, P.; Iov, F.; Blaabjerg, F., Dynamic wind turbine models in power system simulation tool DIgSILENT. Risø-R-1400(EN) (2003) 80 p.

[32] Bialasiewicz, J.; Muljadi, E. RPM-Sim. National Wind Technology Center. November 2006. http://wind.nrel.gov/designcodes/simulators/rpmsim/

[33] J.T.G. Pierik and J. Morren. Validation of dynamic models of wind farms (Erao-3): Executive summary, benchmark results and model improvements. Technical Report ECN-C--07-000, ECN, 2007.
[34] J.T.G. Pierik and J. Morren. Constant Speed Stall Wind Farm Dynamic Model Validation; Alsvik measurements and simulations. Technical Report ECN-C--07-000, ECN, 2007.
[35] J.T.G. Pierik and J. Morren. Variable Speed Pitch Wind Turbine Dynamic Model Validation; JWT measurements and simulations. Technical Report ECN-C--07-000, ECN 2007.
[36] Ana I. Estanqueiro (2007) "*A Dynamic Wind Generation Model for Power Systems Studies*", IEEE Transactions on Power Systems, VOL. 22, NO. 3, AUGUST 2007, pp 920-928.

APPENDIX I: LIST OF SYMBOLS

β	turbine blade pitch angle (rad)
ρ	air density = 1.225 kg/m^3 at 15^{o}C, 1013.3 mbar
λ	tip speed ratio = $\omega_t R/u$
ω_0	Mechanical drive train eigenfreq (locked generator) (rad/s)
ω_b	base angular frequency = 2π50 rad/s for a 50 Hz system
ω_g	generator angular speed (rad/s)
ψ_k	network impedance phase angle (rad)
ω_t	turbine angular speed (rad/s)
θ_t	shaft twist (rad)
A	rotor area = πR^2 (m^2)
C_p	turbine efficiency, function of λ and β
d_m	mutual damping (pu torque/pu speed)
f_0	mechanical drive train eigenfreq (locked generator) (Hz)
f_n	nominal grid frequency (Hz)
H_g	generator inertia (s)
H_t	turbine inertia (s)
J_g	generator moment of inertia (kg·m^2)
J_t	turbine moment of inertia (kg·m^2)
k	shaft stiffness (pu torque/electrical rad)
n_g	gearbox ratio
p	number of generator pole pairs
Q_c	shunt-capacitor (var)
R	rotor radius (m)
S_k	short-circuit apparent power (VA)
S_n	nominal apparent power (VA)
T_g	torque at generator shaft (Nm)
T_t	torque at turbine shaft (Nm)
$u_t(t)$	weighted average wind speed over rotor blades (m/s)
U_n	nominal voltage (V)
Z_b	base impedance (ohm)

APPENDIX II: DATA CONVERSION FORMULAS

$$Z_b = \frac{U_n^2}{S_n} \tag{8}$$

$$\omega_b = 2\pi f_n \tag{9}$$

$$H_t = \frac{0.5 J_t \omega_b^2}{S_n n_g^2 p^2} \tag{10}$$

$$H_g = \frac{0.5 J_g \omega_b^2}{S_n p^2} \tag{11}$$

$$k = \frac{k_m \omega_b}{S_n p^2 n_g^2} \tag{12}$$

APPENDIX III: FIXED SPEED WIND TURBINE DATA

Nominal power, P_n (kW)	180
Nominal voltage, U_n (V)	400
Nominal apparent power, S_n (kvar)	204
Nominal frequency, f_n (Hz)	50
Number of pole pairs, p	3
Stator resistance, R_{1S} (pu)	0,012
Stator leakage reactance, X_{1S} (pu)	0,075
Rotor resistance, R_{2S} (pu)	0,008
Rotor leakage reactance, X_{2S} (pu)	0,171
Magnetizing reactance, X_M (pu)	2,684
Shunt-capacitor, Q_c (kvar)	60*
Generator inertia (incl. high speed shaft), H_g (s)	0,12**
Turbine inertia, H_t (s)	2,77
Shaft stiffness, k (pu torque/electrical rad)	0,46
Gearbox ratio, n_g	23,75
Turbine rotor radius, R (m)	11,63

*The shunt capacitor is rated Q_c =60 kvar, but may not have been in operation at the time of the measurements. Assuming Q_c = 16 kvar provides for a better match between simulations and measurements.
**The generator inertia H_g = 0,12 s does not include the high speed shaft and other high speed rotating parts. Assuming the total high speed inertia to be H_g = 0.24 s provides for a better match between simulations and measurements.

APPENDIX IV: VARIABLE SPEED WIND TURBINE DATA

Nominal power, P_n (kW)	850
Nominal voltage, U_n (V)	690
Nominal apparent power, S_n (kvar)	944
Nominal frequency, f_n (Hz)	50
Number of pole pairs, p	2
Stator resistance, R_{1S} (pu)	0,006
Stator leakage reactance, X_{1S} (pu)	0,072
Rotor resistance, R_{2S} (pu)	0,009
Rotor leakage reactance, X_{2S} (pu)	0,112
Magnetizing reactance, X_M (pu)	4,238
Frequency converter rating, S_f (kvar)	300
Generator inertia (incl. high speed shaft), H_g (s)	0,54
Turbine inertia, H_t (s)	4,17
Shaft stiffness, k (pu torque/electrical rad)	1,16
Gearbox ratio, n_g	57,54
Turbine rotor radius, R (m)	26,00

APPENDIX V: CHALMERS UNIVERSITY OF TECHNOLOGY

At the division of Electric Power Engineering at Chalmers University of Technology electric generating system in wind turbines has been a research subject for many years. The last years of work has also involved grid integration questions. The IEA, Annex XXI, “Dynamic models of wind farms for power systems studies” work suits very well with the research carried out at the division. The international cooperation has strengthened the quality and use of research results. Relevant ongoing, or finished during the Annex-project, research activities are as follows:

1. Stability questions in the transmission grid due to wind power connections, Licentiate thesis May -06, [1].
2. Modelling of wind turbine generators for determination of response to grid disturbances PhD.-thesis June–03, [2].
3. Analysis, Modeling and Control of Doubly-fed Induction Generators for Wind Turbines PhD.-thesis February–05, [3].
4. Large-scale integration of wind energy into the Nordic grid, Licentiate thesis October -06, [4].
5. Grid Reinforcing Wind Turbines, Licentiate thesis May -06, [5].

Chalmers University of Technology (SE) has contribution with 3-5 man-months/year. The main activities included modelling of generators and measurements of wind turbines.

Result from simulations with models of squirrel-cage induction generator and induction generator with slip-rings and converter have been developed and adapted to the data bank of the project. The models have been benchmarked with the other participant models. The main purpose is to use the models in simulation programs for determination of response to grid disturbances and stability questions in the grid.

Chalmers has provided measurement data to the annex data bank as follow:

- Measurements from 4x180 kW fixed speed, stall controlled wind turbines.
- Measurements from wind turbine with rotor cascade and pitch control, 850 kW.

The work has been organized in the following way:

- Work with a common format of wind turbine data and measurement results.
- Interesting results have been extracted from the research projects 1-5 and presented to the Annex.
- Measurements have been evaluated and adapted to a format suitable for the data bank.
- Wind turbine models have been evaluated and benchmark tests have been performed.
- Personal from Chalmers have participated in the working meetings in the Annex.

Chalmers work on modelling of fixed speed wind turbines are described in the licentiate thesis ”Wind Turbine Models for Power System Stability Studies” by Abram Perdana, [4], hereunder Chapter 4 ”Validation of Fixed Speed Wind Turbine Models”. Similar work has also been presented in paper “Validation of fix speed wind turbine dynamics with measured data, [6].

Chalmers work on DFIG modelling are described in the Ph.D.-thesis ”Analysis, Modelling and Control of Doubly-Fed Induction Generator for Wind Turbines” by Andreas Peterson, [3], hereunder Chapter 6 ”Evaluation of Doubly-Fed Induction Generator Systems”. Similar work has also been presented in paper “Modeling and Experimental Verification of Grid Interaction of a DFIG Wind Turbine”, [7].

References

[1] Martins, M. "Voltage Stability Issues Related to Implementation of Large WindFarms", Göteborg, Sweden, Chalmers University of Technology, June 2006.
[2] Petru T. "Modeling of Wind Turbines for Power System Studies", Göteborg, Sweden, Chalmers University of Technology, School of Electrical Engineering, Technical Report No. 449,ISSN 1651-498X, ISBN 91-7291-306-1, June 2003.
[3] Petersson A. "Analysis, Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines", Göteborg, Sweden, Chalmers University of Technology, School of Electrical Engineering, ISBN 91-7291-600-1, 2005.
[4] Perdana A. ”Wind Turbine Models for Power System Stability Studies”, Göteborg, Sweden, Chalmers University of Technology, October 2006.
[5] Ullah, N. R. "Grid Reinforcing Wind Generation", Göteborg, Sweden, Chalmers University of Technology, May 2006.
[6] Martins M., Perdana A., Ledesma P., Agneholm E., Carlson O., “Validation of fix speed wind turbine dynamics with measured data”, Renewable Energy, Volume 32, Issue 8, July 2007, Pages 1301-1316.
[7] Petersson A., Thiringer T., Harnefors L., Petru T., “Modeling and Experimental Verification of Grid Interaction of a DFIG Wind Turbine”, IEEE Transactions on Energy Conversion, Vol. 20, No. 4, Dec. 2005 pp. 878 – 886.

APPENDIX VI: ECN & TU DELFT

Model description
Erao II dynamic models of wind farms (ECN-TUD)

This section gives an overview of the Erao II dynamic models developed by ECN and TUD. The constant speed and variable speed wind turbine model of Erao II have been validated using the Alsvik and JWT measurements in the IEA Annex XXI database. The results of these validations are summarized in this report, a more extensive description of the validation can be found in [1], [2] and [3].

Erao II dynamic models of wind farms

In order to investigate the dynamic interaction of wind farms and the electrical grid, dynamic models of wind farms are needed. The Erao-2 project developed these models and demonstrated their use by designing controllers that cope with grid code requirements and by evaluating different types of electrical systems in wind farms [6], [7]. The component models in the Erao II programme are listed in Table 1.

Table 1: Component models in the Erao II programme

Mechanical and aerodynamic (turbine)	turbine rotor
	mechanical drive train
	tower
	rotor effective wind (pre-processor)
Electrical (turbine, wind farm & grid)	induction generator
	doubly fed induction generator
	permanent magnet generator
	voltage source converter
	transformer
	cable
	synchronous generator
	consumer load
Control (turbine, wind farm and grid)	converter controller (P, Q, V)
	pitch controller
	frequency controller
	voltage controller

The mechanical and aerodynamic models include:

- the wind experienced by the rotor of a single stand alone turbine (rotor effective wind speed, calculated prior to the simulation by a separate pre-processor);
- two types of turbines: constant speed stall (CSS) and variable speed pitch (VSP).

The mechanical and aerodynamic models are described in the ECN-reports [4] and in [5]. The two turbine models consist of submodels for:

- aerodynamic behaviour of the rotor (power and torque coefficients);
- rotating mechanical system (drive train);
- tower (motion of the tower top in two perpendicular directions);

- turbine control system (power limitation by pitch control, yaw control is not included).

The main characteristics of the electrical component models are:

- all electrical components are modelled in dq-coordinates (instantaneous (space) phasors);

- AC-DC converters are modelled by controlled voltage sources.

To obtain dq0-models from abc-models, the Park transformation is used. This transformation is well-known from its use in electrical machine theory. The electrical variables are transformed to a rotating reference frame. This frame is chosen to rotate with the grid frequency. All voltages and currents in the dq0-reference frame are constant in steady state situations. Therefore, modelling in the dq0-reference frame is expected to increase the simulation speed significantly, if variable step-size simulation platform is applied, enabling a large time step during quasi steady-state phenomena. The 0-component is neglected if only symmetrical (balanced) conditions are assumed. The electrical component models calculate instantaneous values and the grid frequency is not assumed to be constant. Since the switching of the power electronic converters is not included in the models, harmonics caused by the switching process are not represented.

Matlab/Simulink implementation

The Erao II programme uses Simulink as simulation platform. Simulink is very suitable for modeling of dynamic systems including complex control systems. With Simulink it is easy to add blade pitch control, yawing, vibration control, generator control and other systems to the dynamic wind turbine model. An additional benefit of using Simulink is that it is based on a graphical user interface, which makes modification and extension of models based on already existing component models very easy.

The mathematical description of the Erao II component models and details on the Simulink implementation can be found in [6].

References

[1] J.T.G. Pierik and J. Morren. Validation of dynamic models of wind farms (Erao-3): Executive summary, benchmark results and model improvements. Technical Report ECN-C--07-000, ECN, 2007.
[2] J.T.G. Pierik and J. Morren. Constant Speed Stall Wind Farm Dynamic Model Validation; Alsvik measurements and simulations. Technical Report ECN-C--07-000, ECN, 2007.
[3] J.T.G. Pierik and J. Morren. Variable Speed Pitch Wind Turbine Dynamic Model Validation; JWT measurements and simulations. Technical Report ECN-C--07-000, ECN 2007.
[4] T.G. van Engelen, E.L. van der Hooft, and P. Schaak. Ontwerpgereedschappen voor de regeling van windturbines.
[5] T.G van Engelen and E.J. Wiggelinkhuizen. ECN design tool for control development; revised points of departure; status report. Technical report, ECN, 2002.
[6] J.T.G. Pierik, J. Morren, E.J. Wiggelinkhuizen, S.H.W. de Haan, T.G. van Engelen, and J. Bozelie. Electrical and Control Aspects of Offshore Wind Turbines II (Erao-2). Volume 1: Dynamic models of wind farms . Technical Report ECN-CX- -04-050, ECN, 2004.
[7] J.T.G. Pierik, J. Morren, E.J. Wiggelinkhuizen, S.H.W. de Haan, T.G. van Engelen, and J. Bozelie. Electrical and Control Aspects of Offshore Wind Turbines II (Erao-2). Volume 2: Offshore wind farm case studies. Technical Report ECN-CX- -04-051, ECN, 2004.

APPENDIX VII: INETI

INPark Dynamic Model: A wind park and local grid detailed model

Abstract
In this appendix the wind park dynamic model developed by INETI is presented together with a base methodology for its application to power system studies. The developed model was applied to the operating conditions of the selected sets of wind turbine experimental benchmark data for steady and transient operation of the grid. The results show a fairly good agreement between experimental and simulated results and indicate the model may be used as a tool for power system studies.

1. Introduction

The model developed by INETI is intended to be a planning tool for "grid integration studies"- these sometimes requested by grid planners when the application for grid connection of wind generating unit is analysed. Another possibility of use is during the design phase of a wind park (e.g. if the connection of a large wind park to a weak PCC - point of common coupling is intended) but also and more relevant to be integrated (in a simplified version) in the TSO models for the power system overall behaviour assessment, before final grid assessment is granted and contracted.

Table 1- Wind generation dynamic characteristics relevant for power systems studies

A. Wind generating unit technology
- type of turbine/electrical generator
- gearbox or gearless transmission
- direct/controlled connection to the grid
- tower shadow and rotor sampling
B. Local conditions (grid at the Pcc) and wind flow
- short circuit power
- interconnection voltage level and regulation
- type of interconnecting transformers (e.g. LTC)
- earth system, stability and coordination of the protections
- turbulence intensity
- spectrum of the wind 3D components (in extreme penetration cases)
- spatial variability of the wind (in extreme penetration cases)
C. Wind park design and control
- number and nominal power of the wind turbines
- turbine operation under wake flow, poor siting
- power collecting system characteristics (X/R) and topology
- possible capacity effects from the cabling system
- added power/voltage control and regulation
D. Numerical simulation of the wind park
- power system steady state
- response to relevant transients

The methodology developed for the application of this model relies on the determination of the factors presented in Table 1. These have the higher influence on the power delivered by wind turbines and Table 1 also identifies the parameters more adapted to their quantification, to act therefore as normalised quality indicators. Therefore, the connection of large wind parks to the grid and the risk assessment of the power system operation with large quantities of embedded wind generation may be divided in the followed steps:

- *Wind turbine type and parameters identification*
  The base technology of the wind turbines used in a wind park determines the type of power quality assessment to be performed. For example, if variable speed wind turbines are to be installed in a wind park these will have to be connected to the grid through back-to-back converter, then being more relevant to estimate the harmonic distortion in the local grid than the dynamic voltage fluctuations. The wind turbine parameters needed to characterize the power quality of a wind turbine are published in IEC 61400-21.

- *Local constraints assessment: grid and wind flow*
  The grid parameters requested to assess the system power quality are available from every electric utility company. If assessed, the wind fluctuations may enable to compute the local wind flow power spectral density. By applying one of the several methods available, e.g. the one based on Shinozuka method [1] included in INPark model or any other similar approach it is possible to generate a broad set of synthetic wind time series characteristic of the wind park future site that can be used as input to dynamic wind park models. If the experimental characterization of the wind power spectral density is not achievable, another possibility is to use a "spectral function" well known from the literature (e.g. Kaimal or Davenport) as an input. Nevertheless, the non-experimented user should be aware of the large errors that may be introduced by this process, and should use it with care only as a rough estimate of the local turbulence. Moreover, it should be noted that the described procedure to obtain the wind fluctuations is only relevant for local power quality studies. For very fast transient assessment, as in the characterization of the RTF response of a wind turbine or park, the time dependency of the wind input is not relevant and may be neglected.

- *Wind park design and control*
  The wind turbine micro-sitting and the optimum use of available terrain determine the lay-out of the park power collecting systems (internal grid). The voltage and power conditioning control both individually by wind turbine and globally by the wind park central unit turn these spatially dispersed wind units into what is nowadays already seen - even if not broadly realized within the sector - as a new generation of power units that are driving the development of new grid codes for most countries (both transmission and distribution), TSOs strategies (forecast techniques, renewable energy systems storage, different "order of merit" in the dispatch centres) and models, and grid operation principles (wind park clustering together with monitoring and control sometimes at distribution grid level).

- *Numerical simulation of the wind park*
  Having fulfilled the three previous items of the method, it is already possible to simulate the behaviour of a wind park.

2. INPark model description

INPark is a wind park and local grid detailed dynamic model that aims to characterize the electric power delivered by a wind turbine. The type of turbines the model fully describes are equipped with a fixed-speed induction generator. The wind turbine model has wind time series as input, hence the voltage fluctuations induced at its terminals are directly induced by the variable and time dependent primary energy source. This time-domain model was developed in late 90's. The model is rather detailed and complex and was initially implemented in modular Fortran 90 routines. Within the activities of International Energy Agency (IEA) Annex 21 research, the model was extended in order to address a wider range of phenomena and situations. Sub-models have been added to describe the wind generation behaviour under transient operation of the power system.

The model includes a set of sub-models, namely the wind correlated synthetic series generating system, the wind conversion system, the reactive power compensation units, the internal electric grid and the characteristics of the local consumers and utility grid. The structure of the WEC model and the interconnection to the grid is illustrated, respectively, in Figure 1 and 2. A full and detailed description of INPark model can be found in [3] and [4].

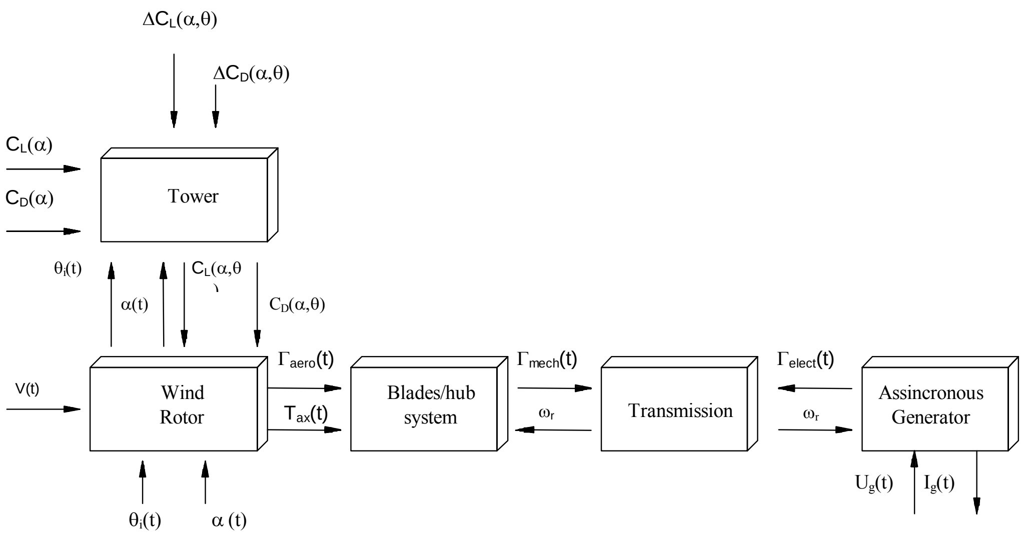


Figure 1 - INPark WEC model

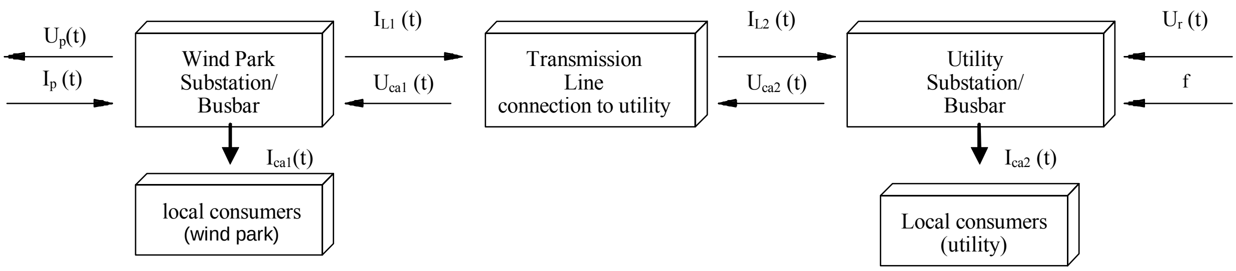


Figure 2 - Model of the grid and local consumers (included in INPark).

2.1 INPark aerodynamic system

2.1.1 <u>Wind rotor sub-model</u>

The INPark aerodynamic behaviour of the rotor is based on the Glauerts's momentum/strip theory having in consideration the following issues:

- tip and hub losses are taken in consideration by the Prandtl-Goldstein model,
- 3D correction of the lift coefficients,
- correction of the lift and drag coefficients in the linear region of the airfoil,
- implementation of the classic or advanced model in the brake region of the airfoil.

2.1.2 Blade – tower interference model

Usually the models that try to describe the tower shadow effect fail to support themselves in a theoretical or even empirical basis, most being just a mere reproduction of experimentally detected oscillations. Therefore, an innovative approach based on the experimental results for circular section cylinders from Zdravkovich [2] was developed and implemented in INPark model. This interference effect is implemented "blade by blade" and analysed independently, thus the computation of the actuating forces on the blades and the momentum generated take also into account this oscillating effect.

2.2 INPark mechanical system

2.2.1 Blades/hub system sub-model

For the purpose on having in consideration voltage and power fluctuations at the wind turbine output it was considered appropriated to include only the 1st mode of the blade-hub joint movement (in both directions) in the torque, rotational speed and mechanical power equations of the shaft. Within this assumption, the blades are modeled as simple rigid bodies, having the entire deformation place in the connection of the blade root to the hub.

2.2.2 Transmission system sub-model

The mechanical transmission is modelled according to the scheme of Figure 3. In this, the high and low speed shafts are represented trough the classic model using as reference the speed and torque from the primary shaft. It is also assumed that all the torsion movement occurs in the primary shaft.

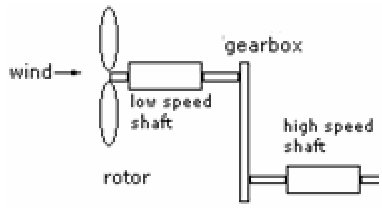


Figure 3 - Scheme of the transmission system.

2.3 INPark electric system

2.3.1 Fixed-speed induction generator sub-model

The induction generator is represented by his *T* equivalent scheme as it is shown in Figure 4. The state equations of the machine are deducted in a (d,q)-coordinate system and, in order to achieve a detailed and more exact generator model, the electromagnetic torque for this particular generator (induction machine) is obtained using the saturation model first developed by Ferreira de Jesus [5] and implemented by Castro [6] for small hydro power plants

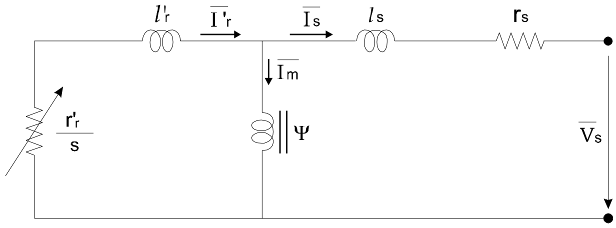


Figure 4 - Equivalent T scheme for the induction machine.

2.3.2 Grid Sub-Model

The local grid is modelled using a common approach: π-equivalents of internal and external lines, ideal step-up transformers and the Thévenin equivalent of grid ($Z_{cc}=R_{cc}+j*X_{cc}$) at of the wind park's PCC (point of common coupling) as it is represented in, where PT refers to the transformation post of the wind park, LT is the transmission line and SEE is the electrical energy system.

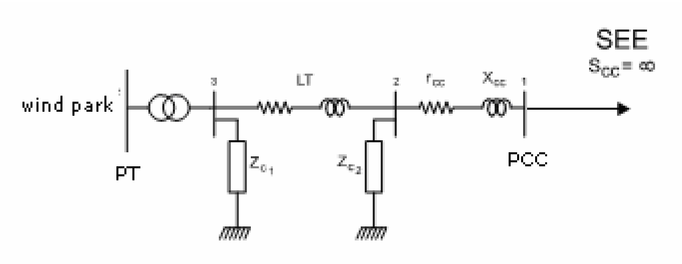


Figure 5 - Local grid scheme.

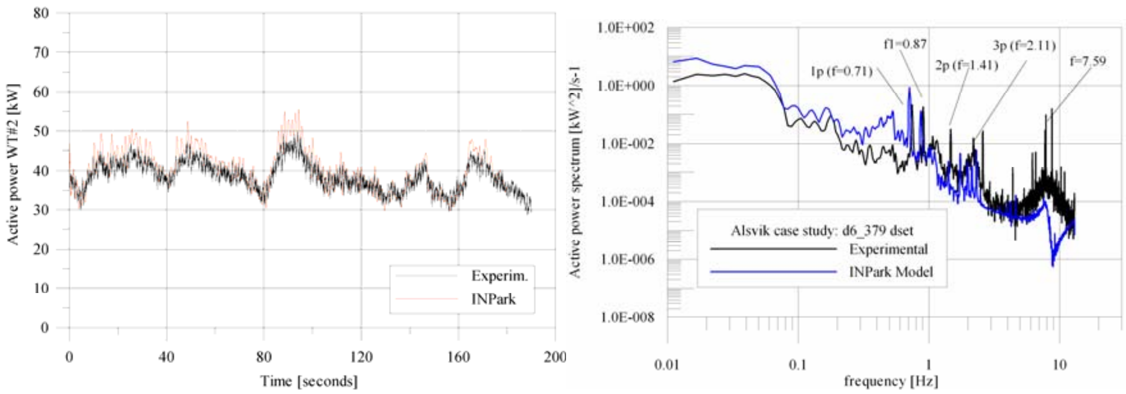
3. INPark applications and results

INPark model can be adapted and applied to the equivalent topology of different wind parks and local grids as it was done for the IEA Annex 21 benchmark cases: Alsvik and Azores case studies. This procedure enabled to simulate dynamically, in steady state and transient operation, the performance of those wind parks and local grids and compare the simulation results to experimental data.

Within the IEA Annex 21 Final Report Azores and Alsvik wind parks were dynamically simulated in steady state and transient operation. Some of INPark simulation results are presented in the Figures 6 to 12.

3.1 Dynamic operation during normal conditions

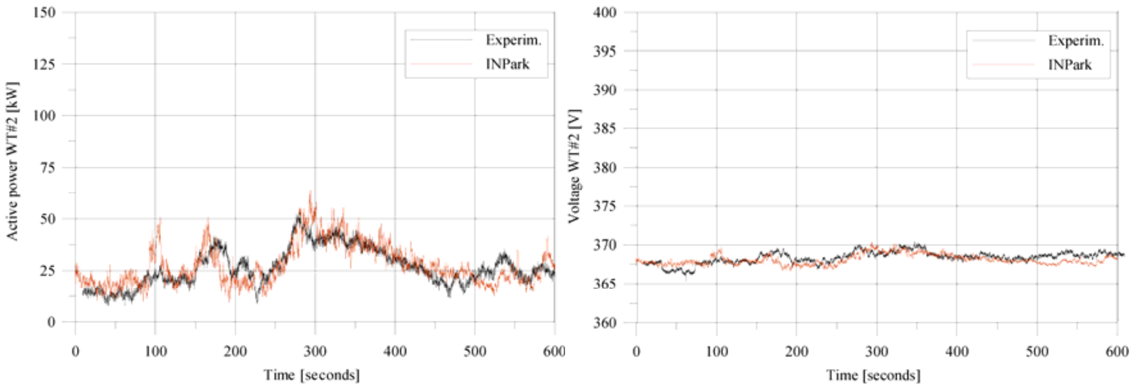
For the operation during normal conditions or grid steady state operation the model input was a wind time series collected for each case study. The local grid of each park was adapted to INPark regarding the specification parameters of each grid component.



a) b)

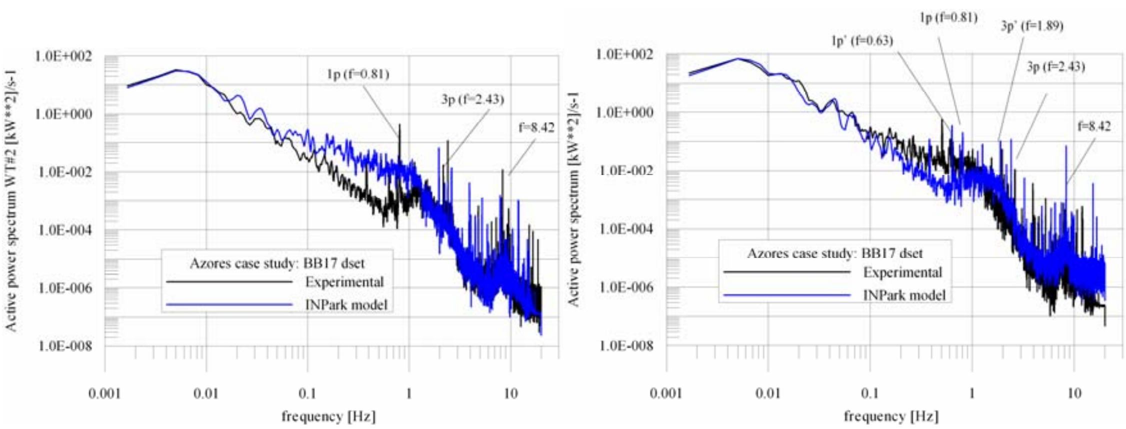
Figure 6 - Simulated and experimental results for wind turbine #2 (Alsvik case study):

a) active power b) active power spectra.



a) b)

Figure 7 - Experimental and INPark simulated for wind turbine #2 (Azores,sample BB17)
a) active power b) voltage at wind turbine terminals



a) b)

Figure 8 - Simulated and experimental active power spectra results (Azores, sample BB17)
a) wind turbine #2 b) MV substation

3.2 Response to a voltage dip (transient operation)

For transient operation only measured data was collected from Alsvik wind park. The model input was the rms voltage time series resultant from the measured voltage phases and with 3 sec.

duration. In this particular case the transient operation was due to the occurrence of a voltage dip at 1.6 sec. and only wind turbine #3 was in operation.

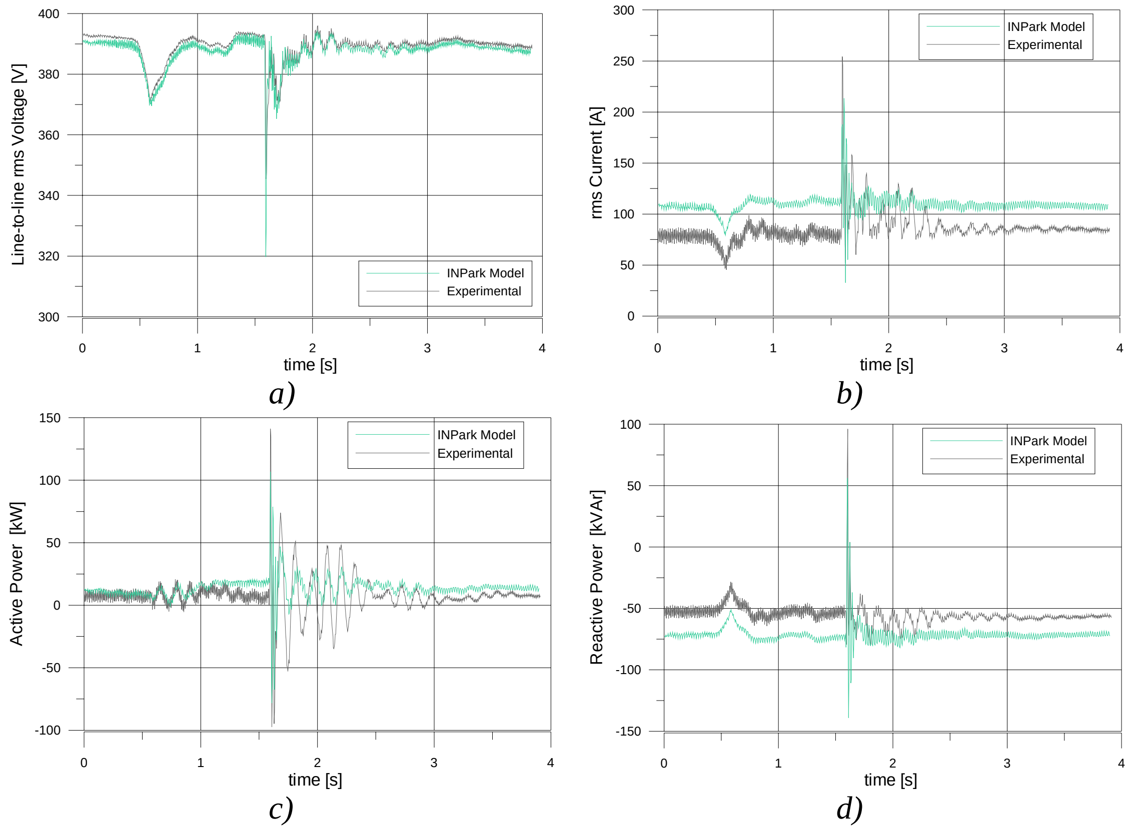


Figure 9 - INPark simulation: a) rms Voltage b) rms Current c) Active Power d) Reactive Power

3.2 Other studies

In order to illustrate the model capabilities of INPark some applications, apart IEA Annex 21 benchmark case studies, are reported below. In [7] and [8] a detailed study can be found.

On Figure it is shown the example of a wind park total active production and reactive power consumption in the interconnecting point (power of common coupling - PCC) while in Figure 11 the voltage dynamic perturbations related to a wind park operation both on park internal and external grid are shown.

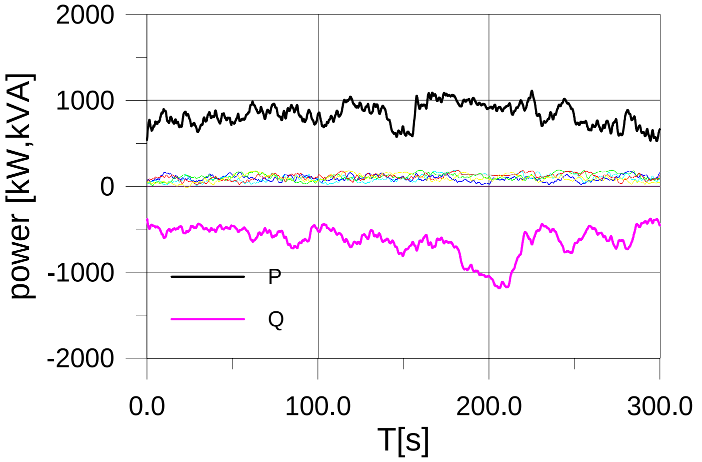


Figure 10 - Active and reactive power flow at the wind park Pcc. (Samos Island wind park).

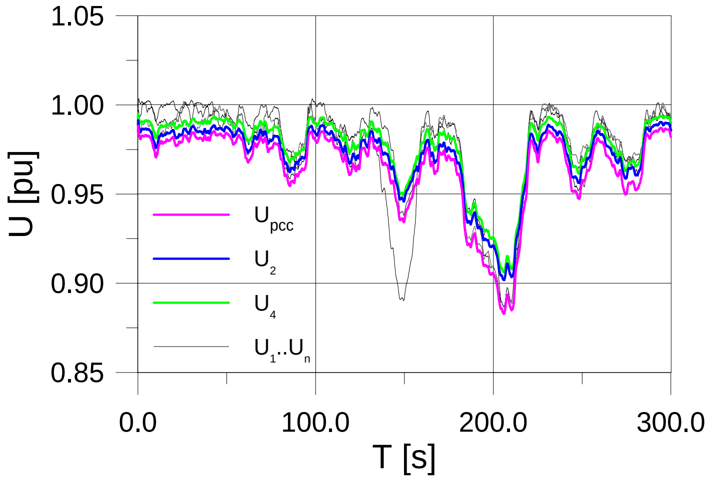


Figure 11 –Voltage fluctuations in two wind turbine (#2, #4) and the park interconnecting busbar (U_{Pcc}) (Samos Island wind park).

The data presented, in the Figure 10 and Figure 11 directly enabled to compute the flicker emission both by each turbine and by the whole park (possible in the feasibility phase of the park) under different conditions of the wind turbulence and the grid and thus assessing the voltage quality of the wind power system.

The next application is also reported in [7] and [8] and illustrates a situation when a wind turbine is connected to the wind park during the cut-in operation.

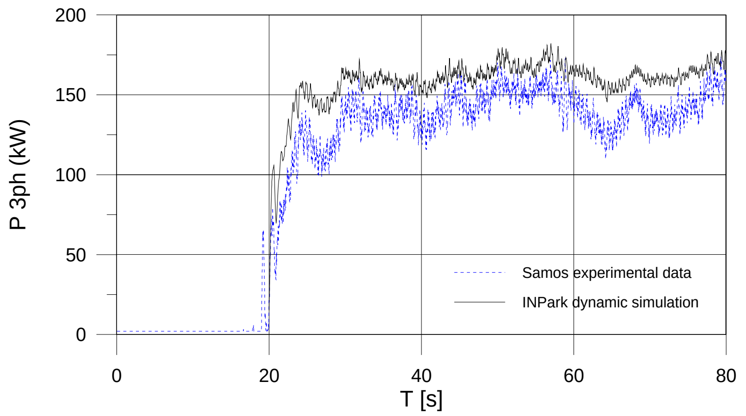


Figure 12 - Wind turbine power output (simulated and experimental) in cut-in (Samos Island wind park).

4. Synthesis and analysis of results

INPark model was applied to the experimental database - including the benchmark test cases of Alsvik- collected by IEA Annex 21 and before it was used in others wind parks operating in steady state and transient mode. The achieved results are in general quite encouraging in what concerns the use of this dynamic model for the power quality assessment and capacity definition of wind parks, in the planning or feasibility phase of these projects.

The main difficulty for the application of detailed wind park models is the difficulty to obtain all the requested input data to characterize the dynamic behaviour of the wind turbines. Nevertheless, even in extreme cases where almost all wind turbine constructive data was obtained from manufacturers catalogues, it is possible to describe the reality in a fair and acceptable form, both in steady and transient state.

The work carried out within IEA IA Wind Task 21 enabled to conclude the major difficulty to validate wind turbine and park models relies on the fact that most experimental campaigns were not designed to the characterization of the wind park's behaviour from the utility grid or power system perspective. That explains the reason why the results of the INPark model agree fairly well with the experimental data for the IEA Azores case study – an experiment conducted for wind grid integration assessment - both in time domain and in frequency domain, this latest considered even more indicative of the model adequacy. Characteristic frequencies corresponding to turbine rotational speed (1p) and blade passage (3p) are clearly identified by the model as well as the turbine response to the wind energy content. Although a fair agreement was also obtained for the IEA Alsvik benchmark case study, in this situation the simulation results show a larger deviation from the experimental values than for Azores. A set of reasons exists for the higher deviations in the Alsvik simulation, among them the fact that not all the data for the INPark model was available (e.g. standard saturation characteristics were used due to non availability of data) and the wind transducers used for this set-up being slow-response common cup anemometers, rather than the sonic 3D fast anemometry used in Azores.

One may conclude stating the results are quite encouraging in what concerns the wide use of dynamic models for the power quality assessment and capacity definition of wind parks, specially useful in the planning phase of these projects. To achieve a more powerful and exacted dynamic model it is of major importance to involve manufactures in this physical modelling activity and conducted a few more power quality-dedicated experimental campaigns..

Property Rights, Acknowledgments and Credits

INPARK software is property of INETI and was firstly developed under the research project PO-MISTRAL, *Modelling Machine Interaction with Regard to Stability and Regulation.*

INPARK development and Axores Experimental campaign was partially funded by the NATO Science for Stability Program.

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References

[1] Shinozuka, M. e C. M. Jan (1972). Digital simulation of random processes and its applications. *Journal of Sound and Vibration*, 25, Nº 1, 111-128.

[2] Zdravkovich, M.M. (1987). The effects of interference between circular cylinders in cross flow. *Journal of fluids and Structures*, 1, 239-261.

[3] Estanqueiro, A.I. (1997) *Wind Park Dynamic Modelling*, Phd Thesis (In Port.), Technical University Of Lisbon/Ist, April 1997, Pp.272.

[4] Ferreira de Jesus, J. M., Estanqueiro, A.I., Saraiva, J.G., Castro, R.M. (2001). NATO SfS PROGRAMME III, PO-MISTRAL Final Report, *Modelling Machine Interaction in a Wind Park with Regard to Stability and Regulation*. January 2001, pp. 113.

[5] Ferreira de Jesus, J.M. (1988a). A model for saturation in induction machines. *IEEE Transactions on Energy Conversion*, 3, Nº3 , p.682-688.

[6] Castro, R.M. (1988). *Gerador de indução: utilização em pequenas centrais hidroeléctricas*, Master Thesis, Instituto Superior Técnico, p.156.

[7] Estanqueiro, A.I. (2002). WIRING Project Final Report (JOR3-CT98-0245) INETI Contribution, Part A: *Theoretical Basis of INETI's INPark Wind Park and Local Grid Models*. Sept, 2002, pp. 57.

[8] Estanqueiro, A.I. (2002). WIRING Project Final Report (JOR3-CT98-0245) INETI Contrib., Part B*: Application of the Models*. Sept, 2002, pp.39.

APPENDIX VIII: NREL

Dynamic Models of Wind Turbine Generator

During the early development of wind power technology, dynamic models of wind turbines were not widely available from commercial vendors. Since then, dynamic models of wind turbines have been developed using different platforms such as Advanced Continuous Simulation Language (ACSL), PSCAD, Matlab/Simulink, PSS/E, PSLF, DigSilent, and many others. Other package programs (FAST, ADAMS) used in wind turbine simulation place an emphasis on mechanical and aerodynamic models. The models developed varied from simple induction generator to doubly fed induction generator and were used to study various cases. NREL developed a package program called Renewable-energy Power-system Modular Simulator (RPM-Sim) to simulate renewable energy technologies, including wind energy systems, photovoltaic (PV), village loads, and diesel generators. NREL also developed modules of several wind turbine types, reactive power compensation, wind power plants, and energy storage using Vissim, ACSL, and PSS/E.

In the past 4-5 years, many commercial vendors have developed dynamic model simulations for different types of wind turbines. NREL has been involved with several working groups that aimed to develop wind turbine models and to make them available to the general public. NREL has also supported various research projects and studies related to utility system integration via collaborations with different entities such as Electric Reliability Council of Texas (ERCOT), Southern California Edison, Oak Creek Energy Systems Inc., Western Area Power Authority (WAPA), Siemens PTI, General Electric, and Western Electric Coordinating Council (WECC).

The formation of IEA Annex XXI has reinforced the importance of the role of dynamic models of wind turbines in expanding the use of wind energy to provide additional diverse energy resources into our power grid. The Annex has provided a forum for worldwide experts in the fields of both dynamic simulation and wind energy to exchange information related to the development, model validation, and data monitoring. The experiences and knowledge brought by the Annex members have been major contributions to the wind energy community, which are disseminated through technical papers presented at the conferences and websites [1].

RPM-Sim

The development of the RPM-Sim package program [2] is based on two different philosophies: (1) RPM-Sim should be able to simulate the impact of a power system grid on a wind turbine generator from the manufacturers' point of view, and (2) RPM-Sim should be able to simulate the impact of a wind generator on the power system grid (i.e. other generators, customer loads connected to the same point of common coupling - PCC) from the utility's point of view.

The RPM-Sim consists of several modules that can be built to form a larger system consisting of several energy sources, energy storage, and loads working in parallels.

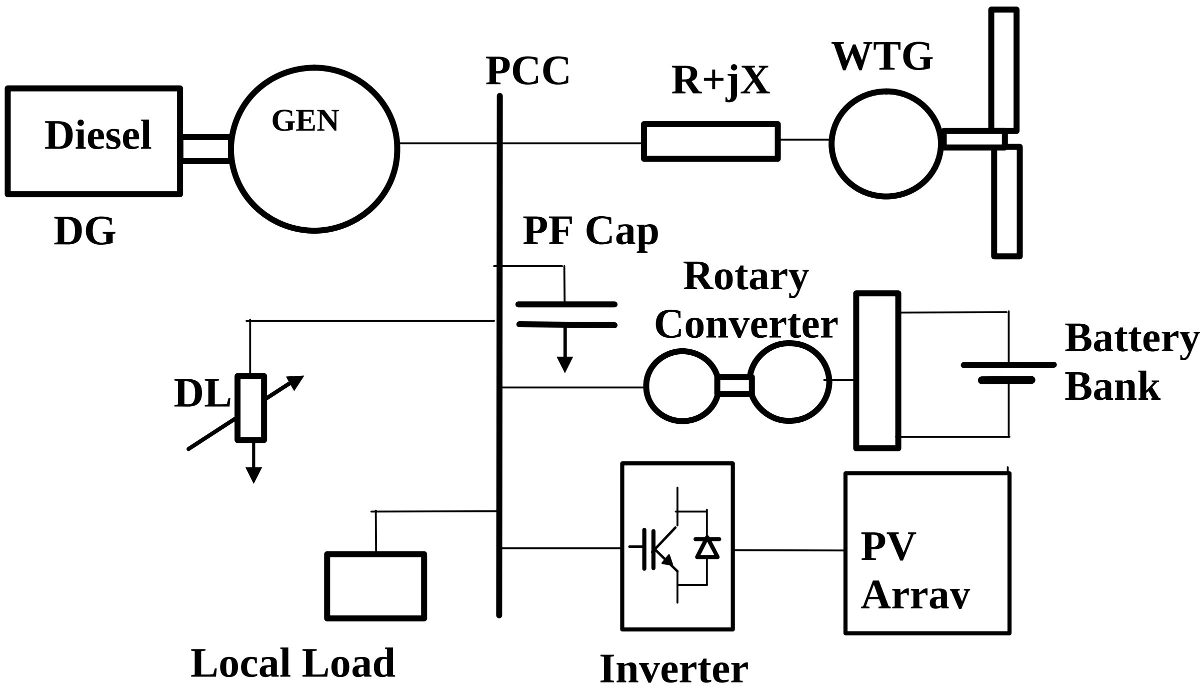


Figure 1. A typical hybrid power system

Figure 1 is an example of a small power system simulated with the RPM-Sim modules. The Point of Common Coupling (PCC) module, which is a node where all power sources and sinks are connected, must be included in every simulation diagram. The diesel generator (DG) module includes a model of a diesel engine, a synchronous generator, an engine speed control block, which generates a fuel/air ratio required to keep the frequency constant, and a voltage regulator, which determines the field current to keep the line voltage constant. The DG module can also be substituted by an infinite bus or other energy sources. The wind turbine generator (WTG) module simulates the two-step conversion of wind power to electrical power. In the first step, the wind power is converted to mechanical power represented by the torque developed by the wind turbine rotor and transmitted to the induction generator through the gearbox. In the second step, the electrical power is obtained. This module includes a model of a transmission line that connects the induction generator with the synchronous generator at the PCC. The power factor correction capacitors (PFC), which are located at the induction generator, are also included. Multiple wind turbines with different wind profiles can be simulated by copying the WTG module. Other modules such as the PV Array, variable loads, dump loads, rotary converter, and energy storage can also be included in the simulation if needed.

Wind Power Plant Model [3]

This work was undertaken with collaboration from Southern California Edison using the PSS/E platform. The wind power plant model was written based a simplification of the generator models. The model is intended to simulate multiple wind power plants (10 and above) as is the case in the Tehachapi, California, area where there are more than 15 wind power plants of different sizes with mostly induction generators. The wind turbine model input includes the wind speed (time series), the parameter of the wind turbines (mechanical dimension and aerodynamic characteristic), and the torque speed characteristics of the generator. To simulate the wind power plant behavior (including the reactive power compensation within the wind power plant), we include the Real Power versus Reactive Power (PQ characteristic) model of the wind power plant measured at the point of interconnection.

Figure 2 illustrates the simplified model concept where the blocks indicate the wind turbine, the wind power plant, and the power grid. Auxiliary devices such as reactive power compensation or energy storage can also be installed at the PCC level.

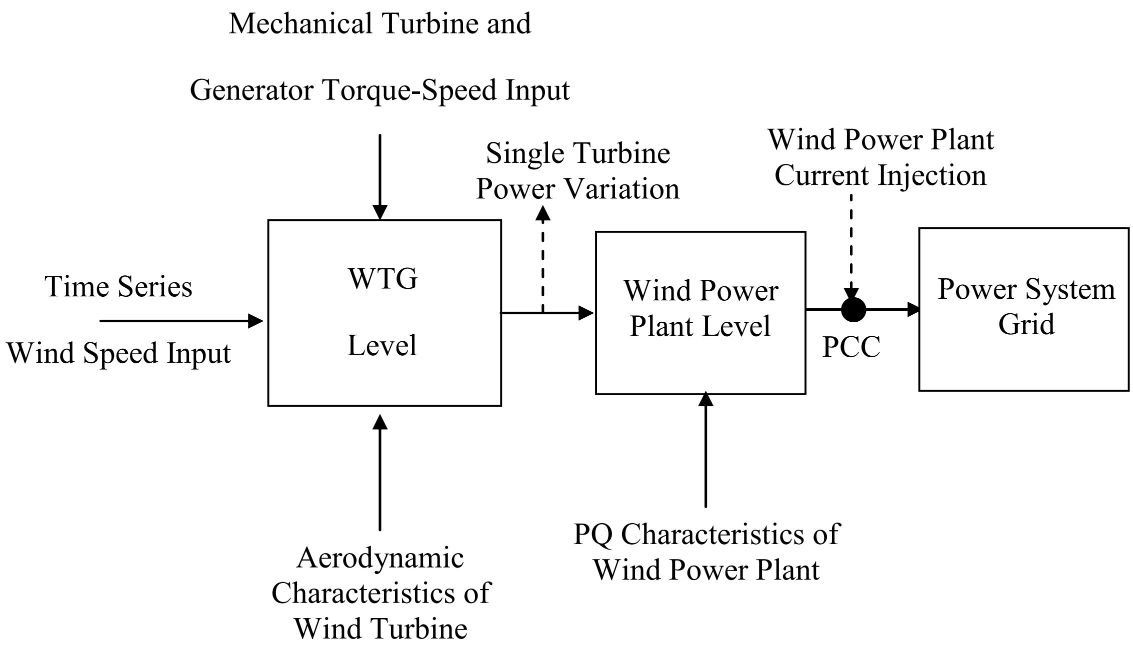


Figure 2. Simplified wind power plant model written on PSS/E platform.

ERCOT and WECC Wind Turbine Generator Models [4-5]

ERCOT pioneered the development of wind turbine generator models when there was an influx of wind power plants installed in Texas. The development was funded by ERCOT and the models were developed by Power Technologies Inc. using PSS/E as the platform. Although these models are available to ERCOT members, they contain information that is considered proprietary that needs to be protected by wind turbine manufacturers. This information is not transparent to the user of the dynamic model. Some wind turbine dynamic models were available from the website of Power Technologies Inc. Other models using PSCAD were also developed under this project.

With the ever increasing number of wind power plants and the fact that many dynamic models contain proprietary information, the need for public domain wind turbine models becomes apparent. The WECC, through its working group (Wind Generator Modeling Group – WGMG) and its task force (Wind Generator Task Force – WGTF), is working to develop a standard dynamic model for four types of wind turbines. The wind turbine types considered are induction generator (traditional wind turbine generator), wound rotor induction generator with rotating adjustable resistor (Vestas' optislip WTG), doubly-fed induction generator (e.g. GE's DFIG variable speed WTG), and full power conversion wind turbines (e.g. Enercon's variable speed WTG). This project intends to make these wind turbine models available to the general public without the need for the users to sign a non-disclosure agreement with the turbine manufacturers. The standard models developed by the WECC will be simplified so that the issues with proprietary information are resolved. This work was undertaken with the collaboration from General Electric (to develop PSLF models) and from Siemens PTI (to develop PSS/E models).

Summary

During the early development of wind power, the level of wind penetration was very low; and there was no significant need to develop wind turbine models. Many utility planners use induction generator models to simulate any type of wind turbine generator. Some planners use a negative load to represent a wind power plant. The dynamic models developed at NREL focused on internal research to improve and to optimize wind turbine operation.

Because the penetration level of wind power has increased dramatically in the past ten years, there is a pressing need to provide dynamic models of wind turbines for transmission planning studies. Misrepresentation of a wind power plant can lead to the wrong conclusion about the potential of wind power plant deployment. If the model used gives a pessimistic result, the power system planners tend to over-build the transmission systems, thus increasing the costs of the development and an excessive budget can discourage wind power acceptance and development. On the other hand, if the model used gives an optimistic result, the power system planners tend to under-build the infrastructure, thus jeopardizing the reliability of the power system operation in the future, and it can be very costly to fix the problems after the system is installed.

NREL has participated in providing wind turbine dynamic models through RPM-Sim and other dynamic models written in ACSL and PSS/E. Later, when many wind turbine models are available from various vendors and sources, NREL will continue to support wind turbine model development by providing technical assistance and other resources necessary to bring the dynamic models developed to the public domain.

RPM-Sim modules have been used to study various projects and the program is available to the general public via an NREL website. The work of ERCOT and WECC on dynamic model development played a major role in providing the public with free access to the dynamic models. Their efforts were supported by many collaborators i.e. utilities, wind power plant developers, wind power plant operators, wind turbine manufacturers, and many researchers worldwide. These collaborators provide various data, i.e., power system grid data, parameter of the wind turbines and monitored data of electrical quantities during normal operation or fault events. The reports generated from these collaborations are available in the public domain [6].

References

[1] Tande, John Olav G.; Muljadi, Eduard; Carlson, Ola; Pierik, Jan; Estanqueiro, Ana; Sørensen, Poul; O'Malley, Mark; Mullane, Alan; Anaya-Lara, Olimpo; Lemstrom, Bettina. "Dynamic models of wind farms for power system studies–status by IEA Wind R&D Annex 21," European Wind Energy Conference & Exhibition (EWEC), London, U.K., November 22-25, 2004.

[2] Bialasiewicz, J.; Muljadi, E. RPM-Sim. National Wind Technology Center. November 2006. http://wind.nrel.gov/designcodes/simulators/rpmsim/

[3] Muljadi, E.; Butterfield, C.P.; Yinger, R.; Romanowitz, H. "Energy Storage and Reactive Power Compensator in a Large Wind Farm," presented at the 42nd AIAA Aerospace Sciences Meeting and Exhibit Reno, Nevada, January 5-8, 2004.

[4] Muljadi, E.; Butterfield, C.P.; Conto, J.; Donohoo, K.; "ERCOT's Dynamic Model of Wind Turbine Generators" presented at the Wind Power 2005 Conference, Denver, Colorado, May 15-18, 2005

[5] Muljadi, E.; Butterfield, C.P.; Ellis, A.; Mechenbier, J.; Hocheimer, J.: Young, R.; Miller, N.; Delmerico, R.; Zavadil, R.; Smith, J.C. "Model Validation at the 204 MW New Mexico Wind Energy Center," presented at the Windpower 2006 Conference, Pittsburgh, June 4-7, 2006. NREL Report No. CP-500-39048.
[6] http://www.nrel.gov/publications/

APPENDIX IX: RISØ

Modelling activities have been carried out as part of parallel projects:

- Simulation and Verification of Transient Events in Large Wind Power Installations: The objective of this project is to assess the ability of dedicated power system simulation tools to predict the response of wind farms to transient events like grid faults in the power system. Simulation of this response is required by the Danish transmission system operators for connection of large (offshore) wind farms directly to the transmissions system. As a case, models for the 6x2 MW wind farm in Hagesholm developed in the power system simulation tools DIgSILENT and EMTDC are used.
- Operation and control of large wind turbines and wind farms: The objective of this project is to analyse and assess the possibilities for control of different types of wind turbines and different wind farm concepts. The potentials of optimising the lifetime/energy production ratio by means of using revised operational strategies for the individual wind turbines are investigated. Models and control strategies for the wind farms are developed, with the aim to optimise the operation of the wind farms considering participation in power system control of power (frequency) and reactive power (voltage), maximise power production, improve the influence on the power quality and limit mechanical loads and life time consumption. Development of models for wind farm controllers, including HVDC transmission
- Stability and control of wind farms in power systems (PhD): The objective of this project is to develop models for assessment of the influence of wind farms on the transient, dynamic and steady state stability of power systems, and to use these models to assess the advantages and limitations of the different wind farm concepts regarding stability.
- Power fluctuations from large offshore wind farms. The objective of this project is to build and validate models for the observed power fluctuations from the two large offshore wind farms in Denmark. The time scale of interest is from a few minutes to a couple of hours.
- Electric design and validation of wind turbines. Models in DIgSILENT for double fed pitch controlled, full scale converter pitch controlled, and (active) stall controlled wind turbines. Models are for normal operation as well as grid fault situations.

Publications

[1] *Jauch, C.; Sørensen, P.; Norheim, I.; Rasmussen, C.*, Simulation of the impact of wind power on the transient fault behavior of the Nordic power system. *Electr. Power Syst. Res.* (2006) **77** , 135-144

[2] *Hansen, A.D.; Michalke, G.; Sørensen, P.; Lund, T.; Iov, F.*, Co-ordinated voltage control of DFIG wind turbines in uninterrupted operation during grid faults. *Wind Energy* (Article in Press)

[3] *Jauch, C.; Cronin, T.; Sørensen, P.; Jensen, B.B.*, A fuzzy logic pitch angle controller for power system stabilization. *Wind Energy* (Article in Press)

[4] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Grid support of a wind farm with active stall wind turbines and AC grid connection. *Wind Energy* (2006) **9** , 341-359

[5] *Sørensen, P.; Cutululis, N.A.; Hjerrild, J.; Jensen, L.; Donovan, M.; Christensen, L.E.A.; Madsen, H.; Vigueras-Rodriguez, A.*, Power fluctuations from large offshore wind farms. In: Nordic wind power conference (CD-ROM). NWPC 2006, Espoo (FI), 22-23 May 2006. (VTT, Espoo, 2006) 5 p.

[6] *Eek, J.; Lund, T.; Marzio, G. Di*, Voltage stability issues for a benchmark grid model including large scale wind power. In: Nordic wind power conference (CD-ROM). NWPC 2006, Espoo (FI), 22-23 May 2006. (VTT, Espoo, 2006) 9 p.

[7] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Power control of a wind farm with active stall wind turbines and AC grid connection (paper and poster). In: Proceedings

(online). 2006 European Wind Energy Conference and Exhibition, Athens (GR), 27 Feb - 2 Mar 2006. (European Wind Energy Association, Brussels, 2006) 6 p.

[8] *Sørensen, P.; Hansen, A.D.; Iov, F.; Blaabjerg, F.*, Modeling of wind farm controllers. In: Proceedings (online). 2006 European Wind Energy Conference and Exhibition, Athens (GR), 27 Feb - 2 Mar 2006. (European Wind Energy Association, Brussels, 2006) 9 p.

[9] *Sørensen, P.; Hansen, A.D.*, Wind power plants - Wind power installations with grid support. In: INDUSCON 2006 (CD-ROM). 7. International conference on industrial applications, Recife (BR), 9-12 Apr 2006. (Organizing Committee, Recife, 2006) 9 p.

[10] *Sørensen, P.; Hansen, A.D.; Thomsen, K.; Madsen, H.; Nielsen, H.Aa.; Poulsen, N.K.; Iov, F.; Blaabjerg, F.; Donovan, M.H.*, Wind farm controllers with grid support. In: Proceedings (CD-ROM). Copenhagen offshore wind conference 2005, Copenhagen (DK), 25-28 Sep 2005. (Copenhagen Offshore Wind, Copenhagen, 2005) 1 p.

[11] *Sørensen, P.; Hansen, A.D.; Lund, T.; Bindner, H.*, Reduced models of doubly fed induction generator system for wind turbine simulations. *Wind Energy* (2005) **9** , 299-311

[12] *Jauch, C.; Sørensen, P.; Jensen, B.B.*, The relevance of the dynamic stall effect for transient fault operations of active-stall wind turbines. *Wind Eng.* (2005) **29** , 353-364

[13] *Jauch, C.; Sørensen, P.; Jensen, B.B.*, Simulation model of a transient fault controller for an active-stall wind turbine. *Wind Eng.* (2005) **29** , 33-48

[14] *Jauch, C.; Matevosyan, J.; Ackermann, T.; Bolik, S.*, International comparison of requirements for connection of wind turbines to power systems. *Wind Energy* (2005) **8** , 295-306

[15] *Sørensen, P.; Hansen, A.D.; Iov, F.; Blaabjerg, F.*, Initial results of local grid control using wind farms with grid support. Risø-R-1529(EN) (2005) 24 p.

[16] *Sørensen, P.; Hansen, A.D.; Thomsen, K.; Buhl, T.; Morthorst, P.E.; Nielsen, L.H.; Iov, F.; Blaabjerg, F.; Nielsen, H.Aa.; Madsen, H.; Donovan, M.H.*, Operation and control of large wind turbines and wind farms. Final report. Risø-R-1532(EN) (2005) 44 p.

[17] *Sørensen, P.; Hansen, A.D.; Iov, F.; Blaabjerg, F.; Donovan, M.H.*, Wind farm models and control strategies. Risø-R-1464(EN) (2005) 63 p.

[18] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Centralised power control of wind farm with doubly fed induction generators. *Renewable Energy* (2006) **31** , 935-951

[19] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Centralised control of wind farm with doubly-fed induction generators. In: Proceedings (CD-ROM). International exhibition and conference for power electronics intelligent motion power quality (PCIM Europe 2005), Nuremberg (DE), 7-9 Jun 2005. (ZM Communications GmbH, Nürnberg, 2005) p. 845-850

[20] *Iov, F.; Hansen, A.D.; Jauch, C.; Sørensen, P.; Blaabjerg, F.*, Advanced tools for modeling, design and optimization of wind turbine systems. *J. Power Electron.* (2005) **5** , 83-98

[21] *Sørensen, P.; Hansen, A.D.; Thomsen, K.; Madsen, H.; Nielsen, H.Aa.; Poulsen, N.K.; Iov, F.; Blaabjerg, F.; Donovan, M.H.*, Wind farm controllers with grid support. In: Proceedings. 5. International workshop on large-scale integration of wind power and transmission networks for offshore wind farms, Glasgow (GB), 7-8 Apr 2005. Ackermann, T.; Matevosyan, J. (eds.), (Royal Institute of Technology, Stockholm, 2005) p. 157-166

[22] *Lund, T.; Eek, J.; Uski, S.; Perdana, A.*, Dynamic fault simulation of wind turbines using commercial simulation tools. In: Proceedings. 5. International workshop on large-scale integration of wind power and transmission networks for offshore wind farms, Glasgow (GB), 7-8 Apr 2005. Ackermann, T.; Matevosyan, J. (eds.), (Royal Institute of Technology, Stockholm, 2005) p. 238-246

[23] *Sørensen, P.; Hansen, A.D.; Thomsen, K.; Madsen, H.; Nielsen, H.Aa.; Poulsen, N.K.; Iov, F.; Blaabjerg, F.; Okkels, B.K.*, Simulation and optimisation of wind farm

controllers. In: Proceedings CD-ROM. 2004 European Wind Energy Conference and Exhibition, London (GB), 22-25 Nov 2004. (European Wind Energy Association, Brussels, 2005) 7 p.

[24] *Hansen, M.H.; Hansen, A.D.; Larsen, T.J.; Øye, S.; Sørensen, P.; Fuglsang, P.*, Control design for a pitch-regulated, variable speed wind turbine. Risø-R-1500(EN) (2005) 84 p.

[25] *Sørensen, P.*, System integration of wind turbines in Denmark. In: System integration of wind turbines. 44. IEA topical expert meeting, Dublin (IE), Nov 2004. FOI-S-1548(SE) (2004) p. 37-44

[26] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Control of variable pitch/variable speed wind turbine with doubly-fed induction generator. *Wind Eng.* (2004) **28** , 411-432

[27] *Jauch, C.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Simulation model of an active-stall fixed-speed wind turbine controller. *Wind Eng.* (2004) **28** , 177-198

[28] *Iov, F.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Simulation platform to model, optimize and design wind turbines. (2004) 45 p.

[29] *Iov, F.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Wind turbine blockset in Matlab/simulink. General overview and description of the models. (2004) 108 p

[30] *Iov, F.; Timbus, A.V.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Wind turbine blockset in Saber. General overview and description of the models. (2004) 41 p.

[31] *Iov, F.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F.*, Analysis of a variable-speed wind energy conversion scheme with doubly-fed induction generator. *Int. J. Electron.* (2003) **90** , 779-794

[32] *Sørensen, P.; Skaarup, J.; Iov, F.*, Dynamic phase compensation of wind turbines. In: Grid integration and electrical systems of wind turbines and wind farms (CD-ROM). Nordic wind power conference 2004 (NWPC 04), Göteborg (SE), 1-2 Mar 2004. (Chalmers University of Technology, Göteborg, 2004) 4 p.

[33] *Iov, F.; Hansen, A.D.; Jauch, C.; Sørensen, P.; Blaabjerg, F.*, Advanced tools for modeling, design and optimization of wind turbine systems. In: Grid integration and electrical systems of wind turbines and wind farms (CD-ROM). Nordic wind power conference 2004 (NWPC 04), Göteborg (SE), 1-2 Mar 2004. (Chalmers University of Technology, Göteborg, 2004) 12 p.

[34] *Hansen, A.D.; Iov, F.; Sørensen, P.; Blaabjerg, F.*, Overall control strategy of variable speed doubly-fed induction generator wind turbine. In: Grid integration and electrical systems of wind turbines and wind farms (CD-ROM). Nordic wind power conference 2004 (NWPC 04), Göteborg (SE), 1-2 Mar 2004. (Chalmers University of Technology, Göteborg, 2004) 7 p.

[35] *Jauch, C.; Sørensen, P.; Bak-Jensen, B.*, International review of grid connection requirements for wind turbines. In: Grid integration and electrical systems of wind turbines and wind farms (CD-ROM). Nordic wind power conference 2004 (NWPC 04), Göteborg (SE), 1-2 Mar 2004. (Chalmers University of Technology, Göteborg, 2004) 6 p.

[36] *Hansen, A.D.; Jauch, C.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Dynamic wind turbine models in power system simulation tool DIgSILENT. Risø-R-1400(EN) (2003) 80 p.

[37] *Sørensen, P.; Hansen, A.D.; Mieritz, M.; Christensen, P.; Bech, J.; Bak-Jensen, B.; Nielsen, H.*, Comparison of simulations of transient events in wind power installations. In: Power and energy systems. IASTED international conference, Marbella (ES), 3-5 Sep 2003. Alvarez, C.; Hamza, M.H. (eds.), (Acta Press, Anaheim, 2003) p. 483-488

[38] *Sørensen, P.; Hansen, A.D.; Christensen, P.; Mieritz, M.; Bech, J.; Bak-Jensen, B.; Nielsen, H.*, Simulation and verification of transient events in large wind power installations. Risø-R-1331(EN) (2003) 80 p.

[39] *Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F.*, Initialisation of grid-connected wind turbine models in power-system simulations. *Wind Eng.* (2003) **27** , 21-28

APPENDIX X: SINTEF

This Appendix describes the main characteristics of wind turbine and wind farm models developed by SINTEF as part of the IEA Wind Annex 21 activities. The description is mainly for PSS/E models, though the same basic principles are also applied for models developed in SIMPOW, Matlab and other. The model development is on-going and according to the continuously development of new wind turbine technology.

The models described include wind turbines with fixed speed asynchronous generator, doubly fed asynchronous generator and direct driven synchronous generator.

WIND SPEED AND AERODYNAMIC TORQUE

A fair wind speed and turbine aerodynamic representation is required for simulating the aerodynamic torque fluctuations. One challenge in this relation is to include the effect of wind speed variations over the turbine area, i.e. an effect that may cause enhanced 3p power fluctuations from wind turbines. This can be done using wind field simulations and detailed blade profile data or, as for the models presented in this report, by application of the following relation:

$$T_t = 0.5\rho A u_t^3 C_p(\lambda,\beta)\omega_t^{-1} \quad (1)$$

Here, u_t is the weighted average wind speed over the three rotating turbine blades, i.e. from a wind field model or for the models of this report by filtering of a single point wind speed time-series, $u_o(t)$.

Fig. 1 shows how the wind speed may vary over the rotor plane of a wind turbine. The wind field will change by time, but not much during the time of one revolution. Hence, the three rotating blades will experience repeated wind speed variations so that $u_t(t)$ will include enhanced fluctuations at three times the rotor frequency (3p). As the wind speed felt by the blades is not varying sinusoidal during one revolution, higher harmonics of the 3p fluctuation is also appearing in $u_t(t)$. Further, because the wind field is changing by time, the period time of the felt wind speed variations will also change, causing enhanced fluctuations not only at integers of 3p, but around integers of 3p. In total, $u_t(t)$ appears significantly different from $u_o(t)$, with energy shifted towards integers of 3p; see also e.g. [1] or [2].

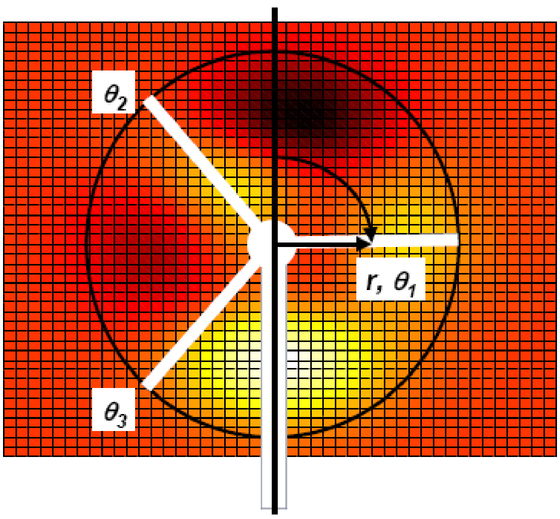


Fig. 1. Example of wind speed variation over rotor plane at a given time, for illustration only.

The dark colour above the hub indicates a local maximum wind speed, and the light colour below the hub indicates a local minimum wind speed. As the wind field changes by time, so will also the location of the local minimum and maximum wind speeds, hence at some other time the local maximum may appear below the hub and the local minimum above the hub.

A quite efficient concept to determine $u_t(t)$ is presented and verified in [3], and for the models presented in this report, this concept is further developed to yield a compact expression. In short, with L^{-1} denoting the inverse Laplace transformation and s the Laplace operator, $u_t(t)$ is determined as a harmonic sum according to (2) below.

$$
\begin{aligned}
u_t(t) &= L^{-1}\{u_o(s)H_o(s)\} \\
&+ \sqrt{2}\sum_{k=1}^{\infty} L^{-1}\{u_{ak}(s)H_{3k}(s)\}\cos 3k\theta_1(t) \\
&+ \sqrt{2}\sum_{k=1}^{\infty} L^{-1}\{u_{bk}(s)H_{3k}(s)\}\sin 3k\theta_1(t)
\end{aligned} \tag{2}
$$

Here, $u_{ak}(t)$ and $u_{bk}(t)$ are uncorrelated stochastic signals, and H_o and H_{3k} are filter transfer functions, one for each harmonic component of $u_t(t)$. The uncorrelated stochastic signals are each generated to yield a PSD in accordance with the Kaimal spectrum, i.e. a common model of turbulent wind speed. The harmonic filter transfer functions are given by (3) and (4) below. The k^{-2} term in (4) provides for a rough approximation only.

$$H_o(s) \approx \frac{0.99 + 4.79cs}{1 + 7.35cs + 7.68(cs)^2} \tag{3}$$

$$H_{3k}(s) \approx \frac{0.0307 + 0.277cs}{1 + 1.77cs + 0.369(cs)^2} k^{-2} \tag{4}$$

The expression for $u_t(t)$ and the filters are generic in the sense that they do not need to be tuned for any particular wind turbine or wind conditions. Only the constant $c=R/u_{avg}$ must be set to reflect the wind turbine rotor radius and the average wind speed of $u_o(t)$.

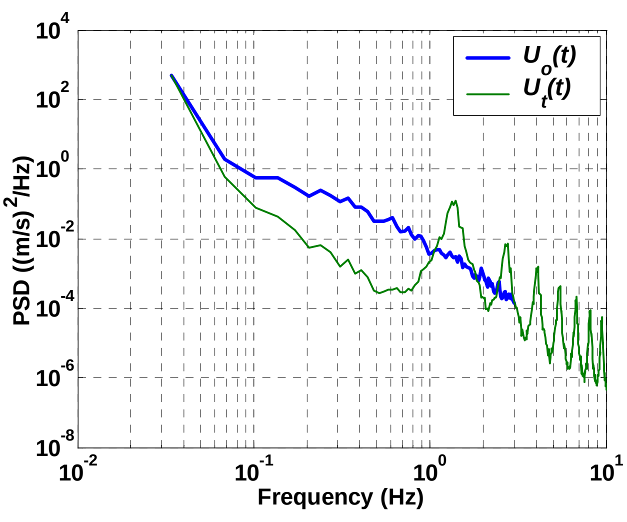


Fig. 2. PSD of input wind speed $u_o(t)$ (thick line) and weighted average wind speed $u_t(t)$ (thin line).

DYNAMIC SIMULATION MODELS

The dynamic simulation models presented here have been implemented in the PSS/E power system simulation tool. A generic model of a wind turbine (called WINT01) has been implemented. This model is used essentially by the three generator models; fixed speed asynchronous generator, doubly fed induction generator and the direct driven synchronous generator.

Wind Turbine Model WINT01

The output of the wind turbine model is mechanical power which is input to the generator model, thus the turbine/generator model set comprises a two-mass model with shaft dynamics modelled.

The wind turbine model is capable of:

- passive stall control
- active stall control
- active pitch control

Input to the turbine model can be one of three; mechanical torque (fixed), wind speed (fixed) or measured wind speed from time-series. The output of the model is the mechanical power, P_{mech}, input to the induction generator model (e.g. CIMTR3). Fig. 3 describes the model in more details.

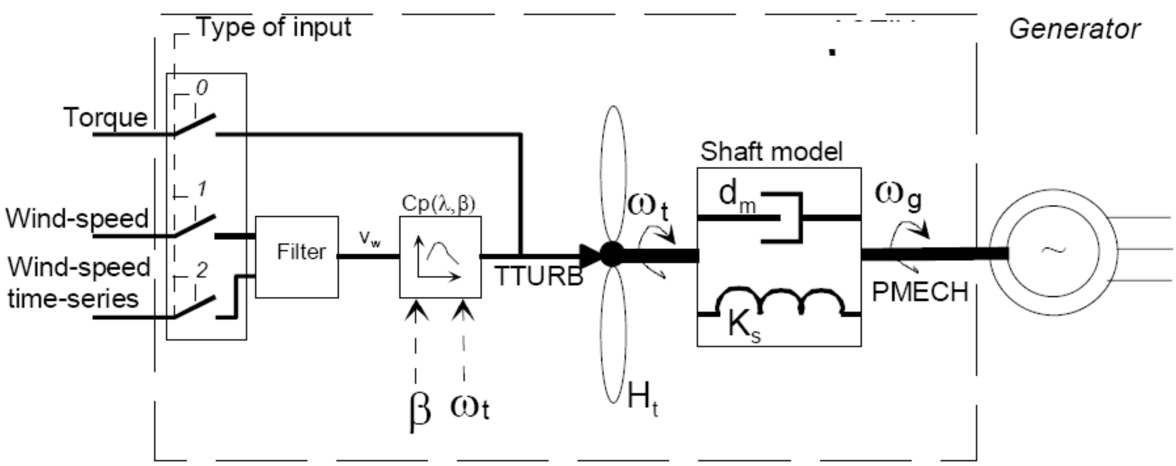


Fig. 3. Schematic diagram of the wind turbine model WINT01.

The turbine torque, T_{turb} is transferred through the main shaft and gearbox to the generator shaft as mechanical torque, T_{mech}. The output from the model is mechanical power (P_{mech}), input to the induction generator model.

When the input to the turbine model is constant torque (i.e. input type 0, see Fig. 3), the turbine torque, T_{turb}, is determined by the power flow calculations.

The wind turbine efficiency coefficient, C_p, is a function of the rotor blades' pitch angle (β) and the tip speed ratio (λ). In the turbine model, a two-dimensional linear interpolation is performed in a $C_p(\lambda,\beta)$ look-up table. The data for the turbine efficiency curve (i.e. the $C_p(\lambda,\beta)$ curve) are read from a text-file of a specific format.

During initialisation, the model reads two data files (if wind-speed time-series input is chosen):
- $u_0(t)$: measured wind-speed
- $Cp(\lambda,\beta)$: Turbine efficiency vs. tip-speed ratio and blade angle

In order to model different wind turbines or wind farms at different locations, the user can choose up to four input files for wind speed and four files for turbine efficiency.

The maximum number of records in the wind speed input file is 6000. Eventually, if the end of the file is reached, the model continues the calculations, but now in the fixed wind speed mode using the wind speed value from the last record of the input file.

The wind turbine efficiency coefficient, $C_p(\lambda,\beta)$, is non-linear. However, linear interpolation does not introduce any significant error when applied within a narrow range around the operating point.

The non-linearity of $C_p(\lambda,\beta)$ is higher for higher wind speeds, i.e. at low λ-values. The resolution of the $C_p(\lambda,\beta)$-data may thus affect the accuracy of this method.

Fixed Speed Asynchronous Generator
The wind turbine model WINT01 is used in connection with a standard asynchronous generator model (CIMTR3 in PSS/E). The basic arrangement is shown in Fig. 4.

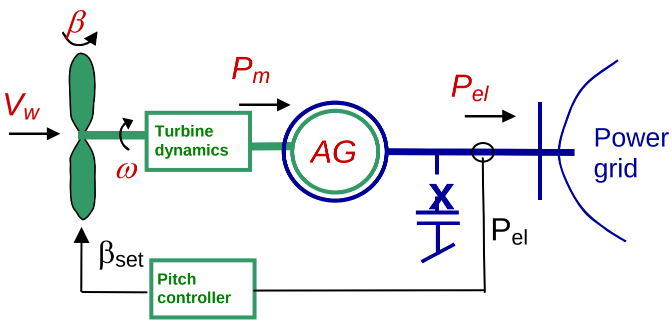


Fig. 4. Configuration of a fixed speed wind turbine with induction generator.

The output of the wind turbine model is mechanical power which is input to the generator model, thus the turbine/generator model set comprises a two-mass model of the shaft dynamics.

The generator model CIMTR3 is a model of an induction generator and is a part of the PSS/E standard library. The CIMTR3 models either a single-cage or double-cage induction generator including rotor flux dynamics. The input to the model is the mechanical power (P_{mech}) supplied by the turbine.

Also, a model representing a fast acting unit for reactive power compensation for enabling the wind turbine generator to maintain a fixed power coefficient ($\cos\varphi$) referred to the 22 kV side of the step-up transformer has been implemented. Basically, this model describes a reactive bus load. The model measures the reactive power flow between two buses and the size of the reactive load is determined as equal to the measured reactive power flowing between the buses, thus eliminating the reactive power flowing through the line (in the case of cosφ = 1.0).

Doubly Fed Induction Generator

In the present section a dynamic model of a doubly fed induction generator (DFIG) with two different control systems is described. The DFIG model using current references for the rotor converter control is labelled DFIGI. The DFIG model using torque and reactive power references for the rotor converter control is labelled DFIG07. DFIG07 is favourable to DFIGI in simulations of large power system, as DFIGI may require very low time steps compared to DFIG07. DFIGI and DFIG07 have been implemented in PSS/E for positive sequence phasors. The stator flux transients are neglected in both models, and in DFIGI also the stator resistance has been neglected. The equations for representing the induction generator used in DFIGI and DFIG07 are similar to those for the induction motor representation for stability studies found in [4, p.300-304].

Fig. 5 shows an overview of the model components in the DFIGI system. The grid side converter is utilized to control the magnitude of the stator voltage, alternatively it can control the amount of reactive power Q_{grid} the turbine delivers to the grid. Due to model simplifications the delivered active power P_{conv} from the grid side converter to the grid is exactly the same as the delivered active power from the rotor to the rotor side converter (the DC-link dynamics are neglected). The rotor side converter controls the speed of the generator in such a way that maximum efficiency of the generator is obtained in the variable speed region of the turbine. Fig. 6 shows an illustration of how the torque reference is set in the different operation modes of the turbine. Further, the rotor side converter controls Q_{grid}. By using stator flux orientation the rotor current components in the d- and q-axis are calculated to represent the correct references for the air gap torque and the reactive power delivered to the grid.

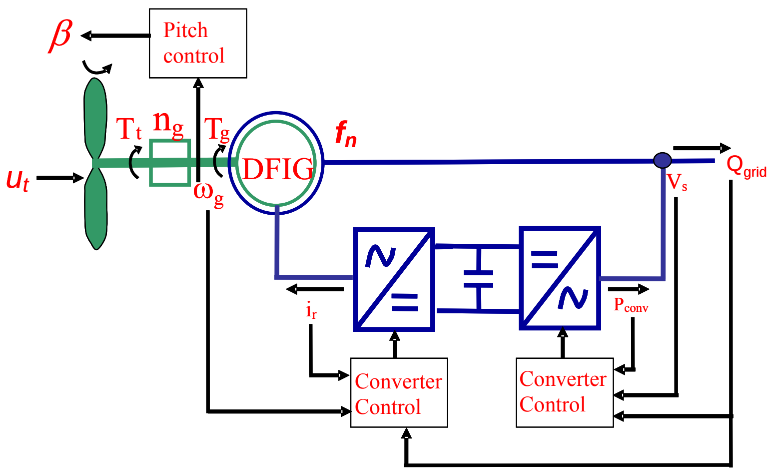


Fig. 5. Wind turbine system with the doubly fed induction generator DFIGI

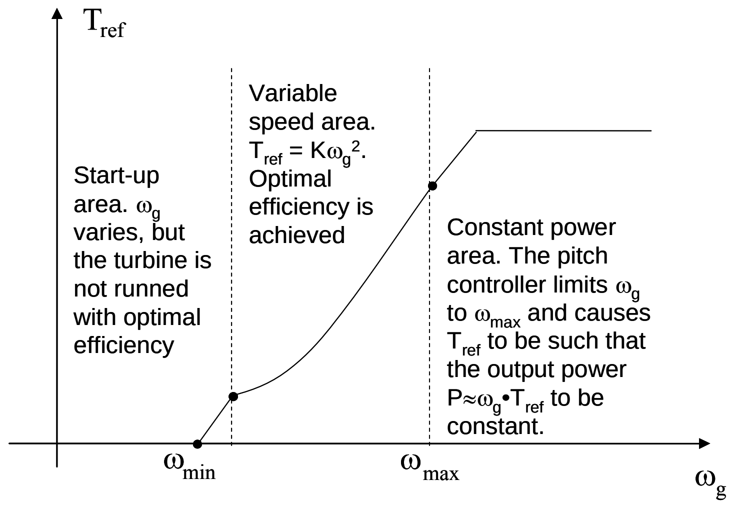


Fig. 6. The torque-speed characteristic of the DFIG

Fig. 7 shows an overview of the model components in the modelled DFIG07 system. In this case the rotor side converter uses the estimated rotor flux and the stator current to calculate the air gap torque. The calculated air gap torque is compared directly with the reference torque which is calculated based on the measured generator speed. The torque reference is set based on the generator speed to obtain maximum efficiency in the variable speed region of the turbine. The d-axis rotor voltage is controlled in order to obtain balance between the reference torque and the air gap torque. The q-axis rotor current is controlled to obtain balance between the reference and the measured value for the reactive power delivered to the grid. The grid side converter is controlled in the same manner as in the case with DFIGI.

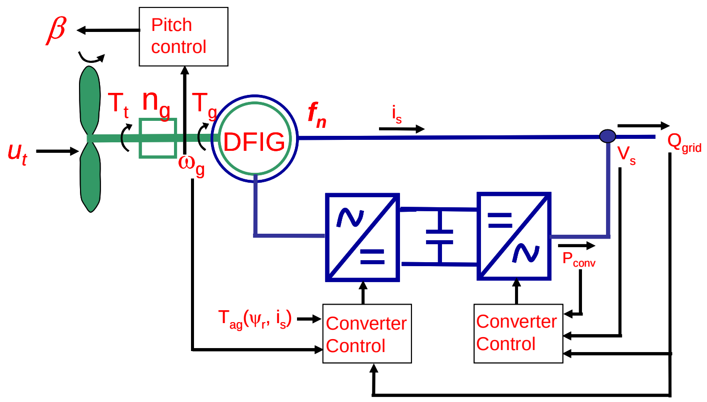


Fig. 7. Wind turbine system with the doubly fed induction generator DFIG07

Direct Driven Synchronous Generator

In the present chapter a dynamic model of a permanent magnet synchronous generator and a full-scale back to back DC-link converter with controllers for a direct driven wind turbine (DDWT) is described. This model is labelled DDSG (Direct Driven Synchronous Generator) and is intended for power system stability studies. It has been implemented for simulations where positive sequence phasors represent the electrical state in the AC network, and specifically in PSS/E. The equations for the permanent magnet generator are similar to those found in [5] when neglecting the stator flux transients. The DC-link voltage varies dependent on the difference between the active power flowing into the generator side converter and the active power flowing out of the grid side converter (it is also possible to define converter losses).

Fig. 8 shows an overview of the model components in the modelled DDWT system. The grid side converter is utilized to control the reactive power exchange between the DDWT system and the grid and to control the DC-link voltage. The generator side converter controls the speed of the generator and the stator voltage of the generator. The pitch controller is active if the generator speed exceeds its maximum allowed value. To model the effect of the permanent magnets a speed varying inner voltage is defined.

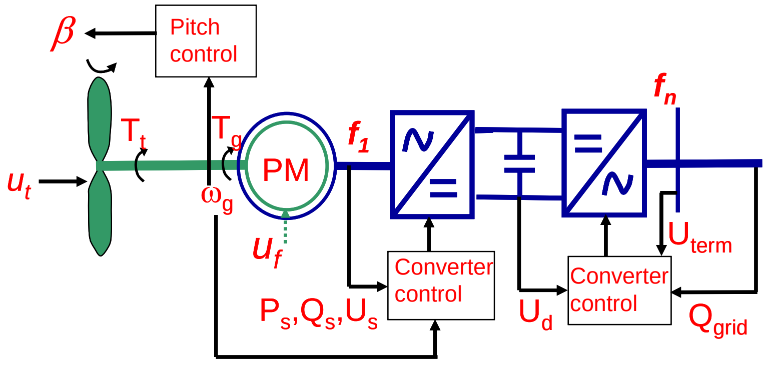


Fig. 8. Direct Driven Wind Turbine system

MODEL VALIDATION

Wind Turbine in Connection with a Fixed Speed Asynchronous Generator Transient operation (response to temporary short circuit)

The transient response of the wind turbine model has been validated by comparing the simulation results with results from two other models. These two models are:

- PSS/E model of a manufacturer specific 2.3 MW wind turbine. This model is made by Shaw Power Technologies International (present Siemens Power Transmission & Distribution, Inc., Power Technologies International) on behalf of the manufacturer in question.
- Induction generator with a turbine (a simple two-mass model), established in the power system simulation tool SIMPOW® from STRI, Sweden.

The input to the models, during these simulations, is fixed turbine torque (TTURB).

A simple grid model has been established, as shown in Fig. 9, for comparing the transient response of the different models.

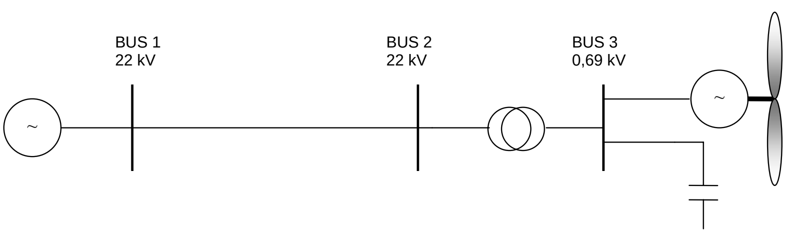


Fig. 9. Model of a simple grid for comparing different wind turbine models.

This model consists of a stiff bus (swing bus, BUS 1), a transmission line between BUS 1 and BUS 2 (22 kV) and a 22/0.69 kV transformer between BUS 2 and BUS 3. The wind turbine is connected to BUS 3 at 0.69 kV together with a fixed capacitor for no-load reactive compensation.

The simulated fault is a 100 ms bolted three-phase short circuit at BUS 2.

The manufacturer specific 2.3 MW model
This model is not a two-mass model, i.e. it does not contain a separate module for the turbine. Instead, the total inertia (i.e. of the generator and the turbine) is inserted in the generator model. Data for the model (turbine and generator) is supplied with the package. Data for the CIMTR3+WINT01 models are supplied by manufacturer.

To compare the transient response of the CIMTR3+WINT01 models with the response of the manufacturer specific model, the WINT01 model has been omitted and the total inertia (i.e. of the generator plus the turbine) has been included in the generator model, CIMTR3. The rated power output of the CIMTR3 model is 2.0 MW, whereas for the manufacturer specific model it is 2.3 MW. The applied parameter values of the models are given in Table **1**.

Table 1: Parameter values for manufacturer specific 2.3 MW and CIMTR3 2.0 MW generator models, respectively.

Parameter	Manufacturer 2.3 MW model	CIMTR3 2.0 MW model
Stator resistance, R_A [Ω]	0.0012	0.0022
Stator reactance, X_A [Ω]	0.0296	0.0376
Rotor resistance, R_1 [Ω]	0.0015	0.0018
Rotor reactance, X_1 [Ω]	0.0110	0.0155
Magnetising reactance, X_M [Ω]	0.6642	0.9209
Generator inertia constant, H_g [s]	5.3 [1)]	0.295
Turbine inertia constant, H_t [s]	-	4.7314

[1)] In this model the total inertia constant of the generator and turbine is included in the generator model.

The transient response, with respect to produced active power, is shown in Fig. 10.

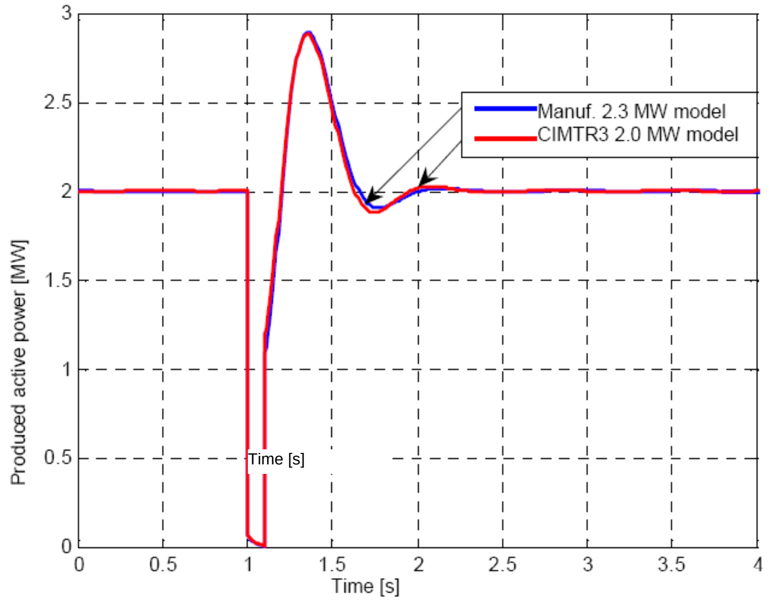


Fig. 10. Transient response, with respect to produced active power, subject to a temporary fault.

There is practically no difference between the responses of these two models. Thus, the generator parameterisation used here (i.e. for the CIMTR3 model) is considered adequate.

One drawback of the manufacturer specific model is the lack of a separate turbine module. This reduces the relevance of using this model for transient stability studies, where oscillations initiated by the two masses oscillating against each other, often dominate the transient response. The CIMTR3+WINT01 models, however, operate together as a two-mass model. The difference is shown in Fig. 11.

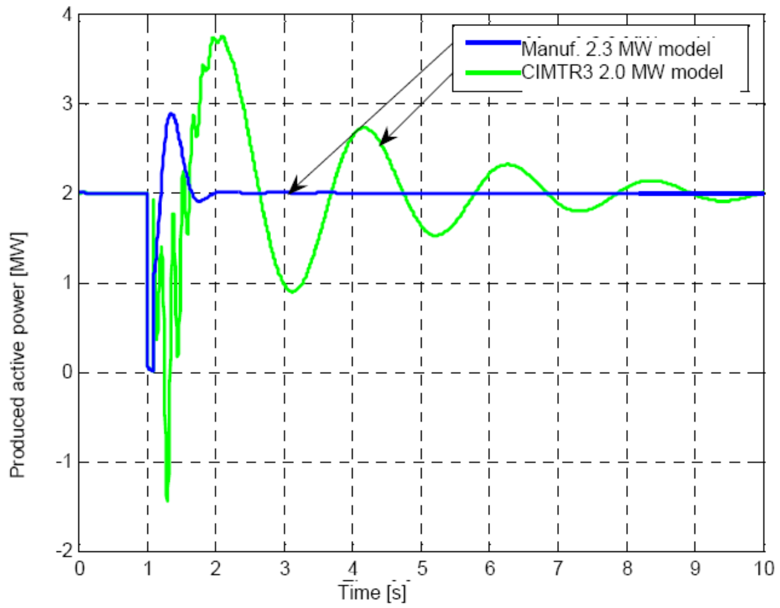


Fig. 11. Comparison of the transient response, subject to a temporary fault, for wind turbine generator models with and without a separate turbine model.

From Fig. 11 the importance of using dynamic two-mass model in transient stability studies is obvious.

Two-mass model in SIMPOW

The CIMTR3+WINT01 two-mass model is validated against a two-mass model established in the power system simulator SIMPOW. This model consists of an induction generator model and a turbine model (represented by it's inertia, shaft stiffness etc.). The model uses the same parameterisation as the CIMTR3+WINT01 model (see Table **1**).

The transient response of the CIMTR3+WINT01 models compared with the SIMPOW two-mass model is shown in Fig. 12 (with respect to produced active power) and Fig. 13 (with respect to the generator rotor speed).

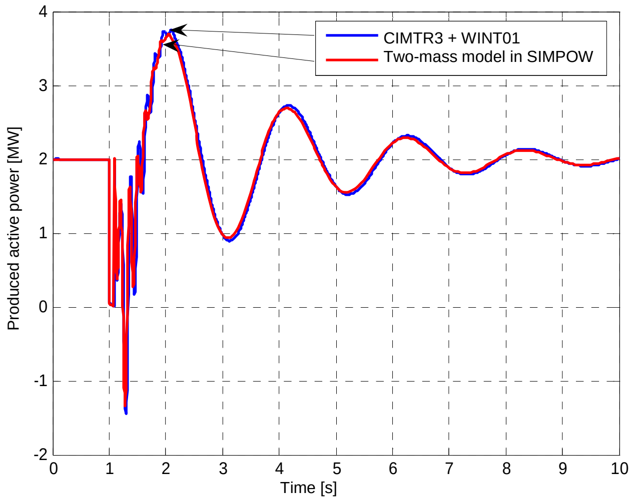


Fig. 12. Comparison of wind turbine models. CIMTR3+WINT01 vs. two-mass model in SIMPOW. Transient response in produced active power subject to a temporary (100 ms) three-phase short circuit at BUS 2.

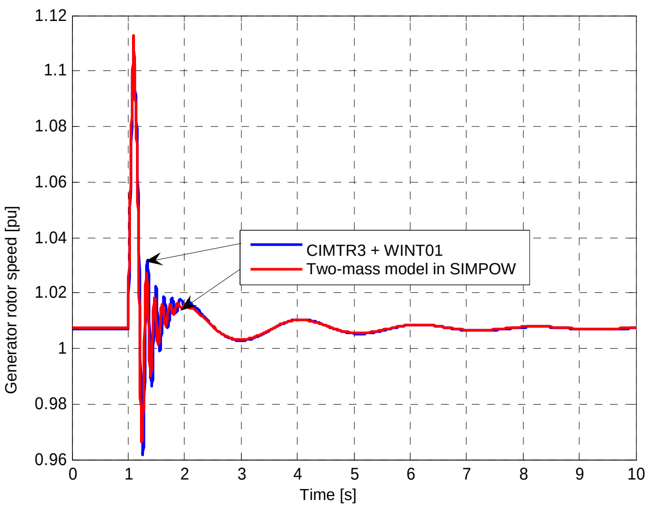


Fig. 13. Comparison of wind turbine models. CIMTR3+WINT01 vs. two-mass model in SIMPOW. Transient response in generator rotor speed subject to a temporary (100 ms) three-phase short circuit at BUS 2.

As seen from Fig. 12 and Fig. 13, there is excellent correspondence between the transient response of the two models.

REFERENCES

[1] L. Kristensen and S. Frandsen, *Model for power spectra of the blade of a wind turbine measured from the moving frame of reference*, Journal of Wind Engineering and Industrial Aerodynamics, vol. 10, pp 249-262, 1982.

[2] J.B. Dragt, The spectra of wind speed fluctuations met by a rotating blade and resulting load fluctuations, in Proc. European Wind Energy Conference 1984, pp 453-458.

[3] P. Sørensen, A. D. Hansen, P. A. C. Rosas, *Wind models for prediction of power fluctuations from wind farms*, Journal of Wind Engineering, vol. 89, pp 9 18, 2001.

[4] P. Kundur, *Power system stability and control*, McGraw-Hill, 1994, ISBN 0-07-035958-X

[5] A.K. Ådnanes, *Torque Analysis of Permanent Magnet Synchronous Motors*, Power Electronics Specialists Conference, IEEE 1991

APPENDIX XI: UNIVERSITY OF MANCHESTER

This Appendix describes the research work conducted by the University of Manchester and its contributions to the activities of the Annex XXI.

The participation of the University of Manchester in the Annex XXI was supported by the UK DTI Future Energy Solutions.

The research work covers the following major topics:

1. Modelling of fixed-speed and variable speed wind turbines based on induction generators
2. Influence of structural dynamic representations of FSIG wind turbines on electrical transients
3. Control of Doubly-Fed Induction Generator-based wind farms for power network support
4. Impact of wind farms on network dynamic and transient stability

These activities are explained in more detailed below.

1. Modelling of variable speed wind turbines based on induction generators [1]

In this investigation the dynamic modelling of large (MW) capacity Doubly Fed Induction Generators (DFIG) wind turbines using Pscad/Emtdc and Matlab/Simulink was addressed. Suitable speed and reactive power controllers were implemented and studies were conducted to observe the performance of the DFIG during power system disturbances such as three-phase faults developing in different points of the network. These studies were used to determine the DFIG's fault current contribution and power converter rating required for fault ride-through capability and protection requirements.

2. Influence of structural dynamic representations of Fixed-Speed Induction Generator (FSIG)-based wind turbines on electrical transients [2]

The relevance of detailed representations of the structural dynamics of FSIG turbines on transient stability studies was assessed using the software Bladed by Garrad Hassan. This assessment aimed to clarify in which situations a single-mass model is sufficient and in which situations a two-mass model or a full turbine model is required. The FSIG performance was evaluated during voltage sags and network frequency variations using different model representations of the rotor dynamics of the wind turbine.

This investigation indicates that combination of both the shaft and the blade flexibilities are important to represent the drive train dynamics. It was found that the structural dynamics have significant influence on the response of the FSIG turbine during a fault and an appropriate representation of both shaft and blades flexibilities are necessary for this type of study. It was illustrated how a three mass model can be used to represent these rotor structural flexibilities. It was observed that a two-mass model, which only takes into account the shaft flexibilities provides a benign response that does not correspond with the actual response obtained with full representation of the rotor dynamics. The use of this two-mass model may obscure the analysis of dynamic interaction between the mechanical and electrical systems as the true dominant oscillation of the rotor dynamics is not represented. In the case of network frequency variations it was found that as the rate of frequency change is slow the structural flexibilities do not have significant influence on the FSIG performance, and so the use of a single-mass model is suggested for this type of study.

3. Control of Doubly-Fed Induction Generator-based wind farms for power network support [3]-[6]

It is well recognised that many large wind farms will employ Doubly Fed Induction Generators (DFIGs) variable speed wind turbines. In this investigation, models of DFIG wind turbines and their control schemes have been developed and implemented in Matlab/Simulink, PSCAD/EMTDC and IPSA. A review of existing DFIG control schemes and an assessment of their capabilities and dynamic performance was conducted. A novel control scheme for DFIGs to enable them to provide support to power system operation was also designed and implemented in Simulink using a generic network model that comprises mixed conventional synchronous and wind generation. This new controller provides a DFIG-based wind farm with operational and control capability that is compatible with conventional power stations. This could facilitate Grid Code-compliant connections of large DFIG wind farms.

A. Generic network model

A generic network model (Figure 1) comprising both wind farm and conventional thermal generation was designed to perform the DFIG control studies, and to assess power system dynamic stability. Generator 1 can represent synchronous generators and generator 2 can represent a wind farm employing either FSIG or DFIG wind turbines. Generator 3 represents the main system. Although not proposed as a detailed analogue, the system in some ways can be considered representative of the English-Scottish network, with a mixed generation Scottish system transporting power to the larger system of England and Wales.

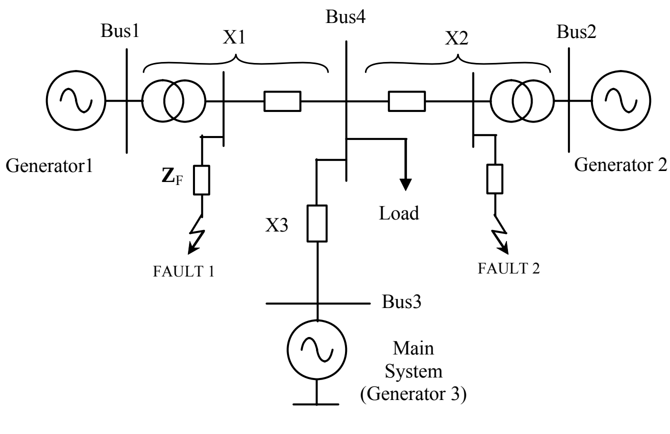


Figure 1. Generic network model.

B. New Flux Magnitude and Angle Controller (FMAC) for DFIG-based wind farms

The new DFIG controller designed in this project is shown in Figure 2. This new controller is based on rotor flux magnitude and angle control, and is therefore identified as Flux Magnitude and Angle Controller (FMAC). The DFIG-FMAC controller emulates the performance of a conventional synchronous generator by incorporating three additional control signals (auxiliary loops), which have the following functions:

- Auxiliary loop 1 provides the DFIG with the capability of emulating the synchronising power characteristic of a synchronous generator.
- Auxiliary loop 2 enables the DFIG to contribute positively to damping of system oscillations (power system stabiliser behaviour).

- Auxiliary loop 3 gives the DFIG the functionality to provide short-term frequency support following loss of generation.

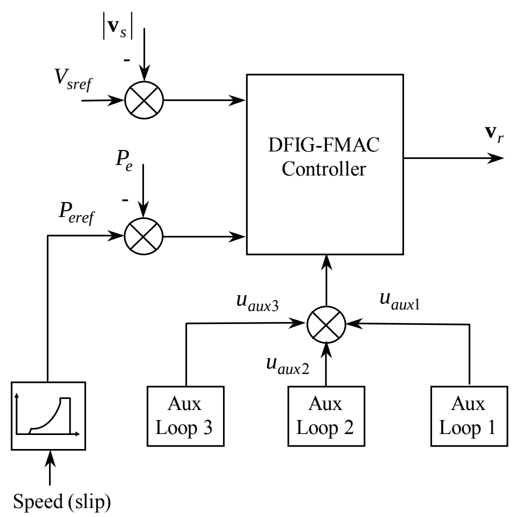
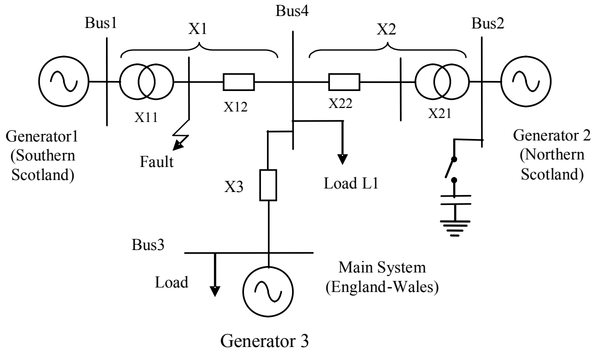


Figure 2. New DFIG-FMAC controller block diagram.

4. Impact of wind farms on network dynamic and transient stability [7]

The interaction between bulk wind farm generation and conventional generation, and its influence on network dynamic characteristics were investigated. A simple generic model (Figure 3) considered representative of the UK network was used for the studies. Time response simulations and eigenvalue analysis were used to establish basic transient and dynamic stability characteristics. The wind generation was provided either by wind farms based on FSIGs or DFIGs.



Operating situations (fixed power P1 of Generator 1)

	Generator 1		Generator 2	
Generator 2 capacity factor f2	Nominal rating (MVA)	Power output (MW)	Nominal rating (MVA)	Power output (MW)
f2 = 1	2,800	2,520	2,400	2,240
f2 = 2/3	2,800	2,520	1,600	1,500
f2 = 1/3	2,800	2,520	800	750
f2 = 1/10	2,800	2,520	240	224

$$\text{capacity factor f2} = \frac{\text{Installed Capacity}}{\text{Full Capacity}}$$

Figure 3. Generic network model and operating conditions considered for the studies shown in this section.

Eigenvalue studies were conducted on the generic network to establish dynamic stability characteristics and to observe the way that stability is influenced as the wind generation capacity (provided by generator 2, DFIG-based wind farm) is increased to its full capacity (2400 MVA - 2240 MW). The situations considered correspond to values of f2=1/10, f2=1/3, f2=2/3 and f2=1, and the rating and power of generator 1 were kept fixed for all the operating situations considered, as shown in Figure 3.

By way of example, Figure 4 presents the dominant eigenvalue loci for the operating conditions considered. The results are shown for both DFIG with basic control only and DFIG with the PSS control loop. In both cases it can be observed that the dominant eigenvalue always lies in the left half of the complex plane and that it is shifted to left as the capacity factor f2 is increased. When the DFIG is provided with the PSS, for each case considered a considerable additional shift to the left of the dominant eigenvalue is seen to be produced, indicating that the PSS can significantly contribute to enhancing network damping and dynamic stability margins.

The studies conducted on the simple generic model indicate that:

- FSIG-based wind farms can contribute significantly to network damping, but are vulnerable to network faults.
- DFIG-based wind farms employing conventional control schemes contribute positively to system damping, although to a lesser extent than FSIGs.
- A DFIG-based wind farm is capable of providing a superior transient performance to that of a conventional synchronous generator following a system fault, as long as suitable fault ride through capability is provided.
- The results generally indicate that in terms of the expansion of renewable energy in mixed generation networks, wind generation based entirely on FSIG-based wind farms would make the network vulnerable to system faults, would restrict generation capacity and pose operational problems.

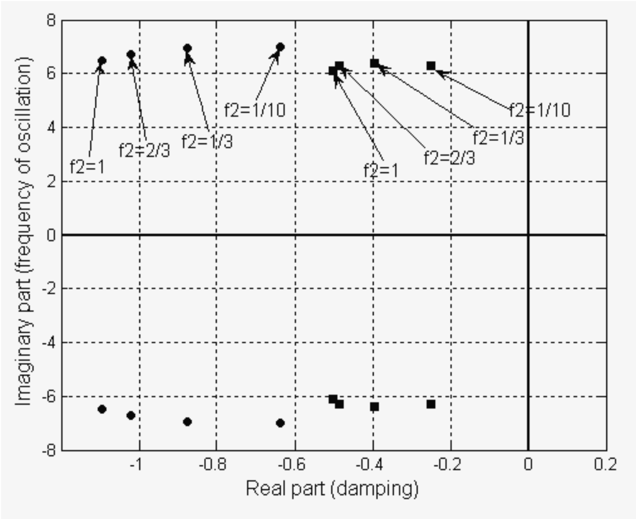


Figure 4. Influence of DFIG size and PSS control loop on the dominant eigenvalue of the network. The DFIG operates in every case considered with a slip of $s = -0.2$. (With PSS •; without PSS ▪)

5. References

[1] Anaya-Lara, O., Wu, X., Cartwright, P., Ekanayake, J. B., and Jenkins, N.: "Performance of doubly fed induction generators (DFIG) during network faults," Wind Engineering, Vol. 29. No. 1, pp. 49-66, 2005.

[2] Anaya-Lara, O., Ramtharan, G., Bossanyi, E. and Jenkins, N.: "Assessment of structural dynamics for model validation of induction generator-based wind turbines," Proceedings of the European Wind Energy Conference EWEC 06, February 2006.

[3] Anaya-Lara, O., Hughes, M., Jenkins, N.: "Generic network model for wind farm control scheme design and performance assessment," Proceedings of the European Wind Energy Conference 2004 (EWEC'04), London, UK, November, 2004.

[4] Anaya-Lara, O., Hughes, F. M., Jenkins, N., and Strbac, G.: "Rotor flux magnitude and angle control strategy for doubly fed induction generators," Wind Energy, Vol. 9. No. 5, pp. 479-495, June 2006.

[5] Hughes, F. M., Anaya-Lara, O., Jenkins, N., and Strbac, G.: "Control of DFIG-based wind generation for power network support," IEEE Transactions on Power Systems, Vol. 20, No. 4, pp. 1958-1966, November 2005.

[6] Hughes, F. M., Anaya-Lara, O., Jenkins, N., and Strbac, G.: "A power system stabiliser for DFIG-based wind generation," IEEE Transactions on Power Systems, Vol. 21, No. 2, pp. 763-772, May 2006.

[7] Anaya-Lara, O., Hughes, F. M., Jenkins, N., and Strbac, G.: "Influence of wind farms on power system dynamic and transient stability," Wind Engineering, Vol. 30, No. 2, pp. 107-127, March 2006.

APPENDIX XII: UNIVERSITY COLLEGE DUBLIN

The Energy Research Center (ERC) at University College Dublin (UCD) have contributed to Annex XXI through works carried out as part of a project funded from Sustainable Energy Ireland (SEI) and supported by national utilities.

This appendix gives an overview of the works carried out at the ERC in support of Annex XXI. Further details on the models described in this Appendix may be found in the published works that resulted from the ERCs participation in Annex XXI detailed at the end of Appendix XII.

1. Model development environment

Wind-turbine model development was carried out using Matlab/Simulink. This package is well suited for developing wind-turbine models from first principles. Matlab is a high performance language for technical computing that includes functions for numeric computation, data analysis, algorithm prototyping, system simulation and application development. Simulink is a window oriented dynamic modelling package built on top of the Matlab numerical workspace. Using Simulink, simulations of linear, nonlinear, continuous-time, discrete-time, multi-rate, conditionally executed, mixed-signal and hybrid systems may be constructed.

The advanced numerical capabilities built into Simulink provided an excellent simulation engine for development of nonlinear wind-turbine models. Off-line analysis and simulation control including pre and post data processing was also performed using the Matlab environment. The choice of this particular software tool for model development in this project was due to the extensive previous dynamic system modelling experience attained by the project team using this tool and the suitability of this modelling environment for the development of wind-turbine model.

2. Wind-turbine model development

Figure 1 shows three of the most common wind-turbine technologies used in modern wind-turbines. The research undertaken at UCD concentrated on model development of the fixed speed squirrel cage design and the variable speed doubly fed designs shown in the figure.

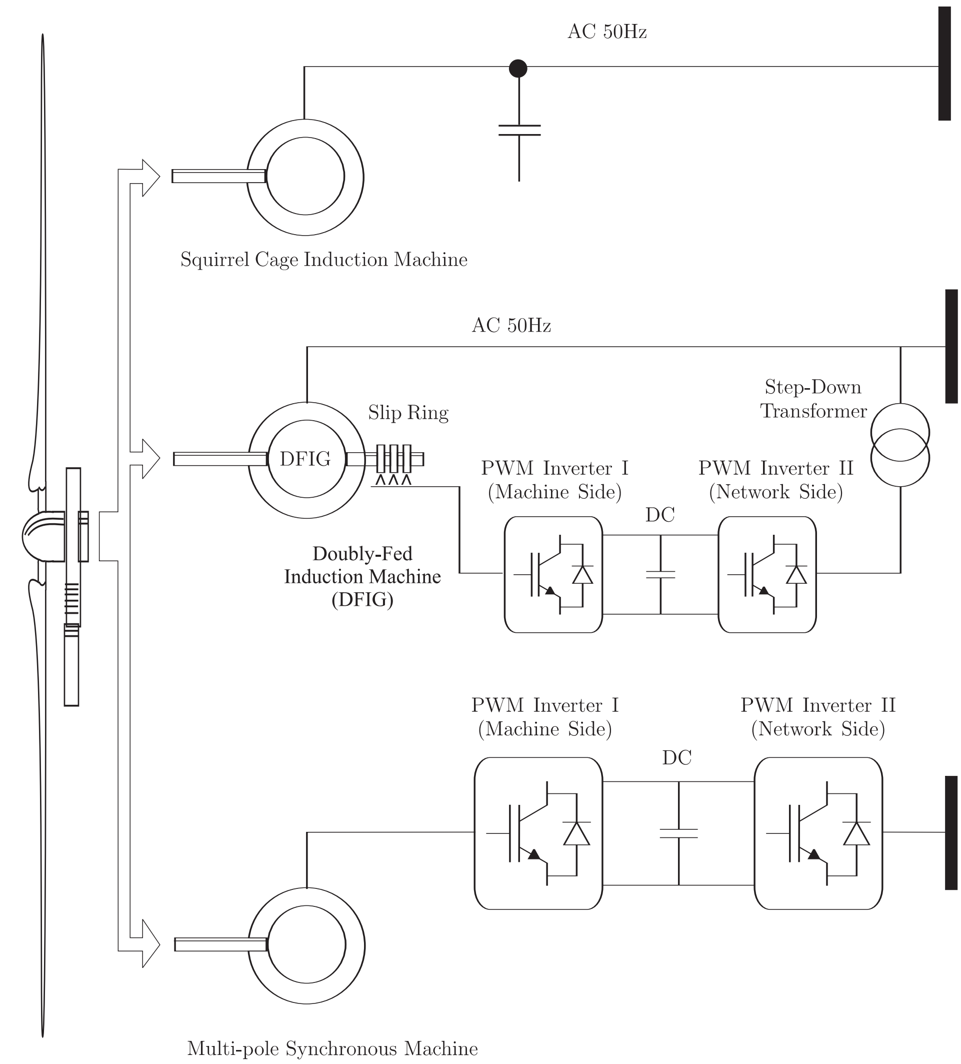


Figure 1.Common wind-turbine topologies

The wind turbine models were developed in varying degrees of accuracy.

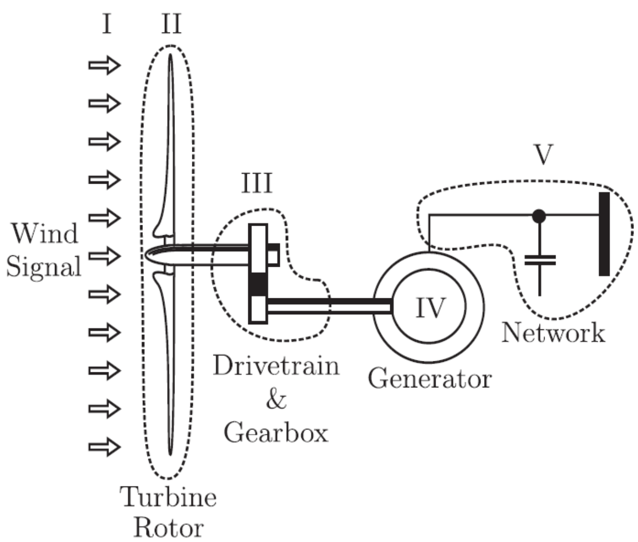


Figure 2.Components of the fixed-speed model

The five main components of the developed models are:

1.10 Wind Signal Model
2.10 Turbine Rotor Model, Including Pitch Actuation
3.10 Drive-train & Gearbox Model
4.10 Generator Model
5.10 Network Model

Apart from the generator model, both the fixed and variable speed models share the above components.

(i) Wind Signal Model
The stochastic wind signal used in many cases as the input to the model is calculated offline using a Kaimal spectrum and simple method using the summation of N unique sinusoidal components of random phase. The deterministic contribution due to mean wind-speed is added, resulting in an accurate point wind-speed model. The point wind-speed is averaged over the swept area of the rotor, by low pass filtering the generated wind signal.

(ii) Turbine Rotor Model, Including Pitch Actuation
The following equations were modelled in Simulink to represent the turbine rotor

$$T_a = \frac{1}{2}\pi\rho C_t(\lambda,\beta) R^3 v_w^2$$

$$\lambda = \frac{\omega_t R}{v_w}$$

$$C_t(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda}$$

These equations were interconnected to provide the aerodynamic torque as a function of supplied wind-speed, rotational speed and blade pitch. The performance coefficient C_p is obtained from a 2D lookup table. A pitch controller may be introduced by varying the blade angle β as a function of the turbine operating point.

(iii) Drive Train and Gearbox Model
A two mass shaft model illustrated in Figure 3 was developed for inclusion in the wind turbine model

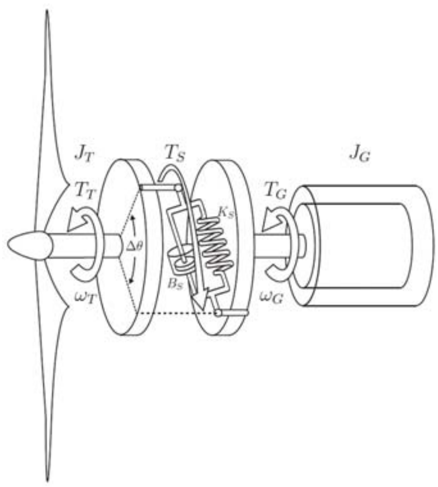


Figure 3.Drive-train model

This model was implemented using the following equations:

$$T_S = T_T - J_T \frac{d\omega_T}{dt}$$
$$T_S = J_G \frac{d\omega_G}{dt} - T_G$$
$$T_S = K_S(\theta_T - \theta_G) + B_S(\omega_T - \omega_G)$$

which relate the speed of rotation of the turbine and generator shafts to the torque at the turbine rotor and generator. A simple first order shaft model was also developed where no flexibility in the drive train is allowed.

(iv) Generator Model

The generator models are the primary components which distinguish the fixed from the variable speed models. A variety of wind-turbine models were developed during the course of ERCs Annex participation. These vary from fixed speed induction machined models which assume no generator dynamics to 5^{th} order models which represent the stator and rotor flux dynamics. Doubly fed induction machine models were also developed which include current controllers in the rotor circuit. These models were further developed to produce reduced order DFIG models which are significantly simpler in their implementation than the standard approach. Both the fixed and variable speed models developed as part of the project are described in detail in [1-7]

(v) Network Model

The network model developed is based on PI and T representations of a power system. These models are based on the differential equations which describe the current voltage relationships of capacitors and inductors which may be interconnected to form PI and T models and further interconnected to produce a model of a section of the power system. The methodology allows balanced conditions to be examined using the developed models. This approach however does not allow for analysis of unbalanced conditions.

3 Scenario Investigation

The models developed as part of the ERCs participation in Annex XXI were used predominantly to examine phenomena of interest to the Irish transmission system operator in the context of increasing penetrations of wind energy. The models were particularly appropriate for examining the effects of increasing penetrations of wind-energy on the control of system frequency in the Irish system. The detailed usage of the developed model in examining both the inertial response of wind turbines and the general and the effects on frequency control of increasing penetrations is explained in the refereed papers below which have been produced as a result of the ERCs participation in Annex XXI.

International refereed journal papers

[1] Mullane, A. and O'Malley, M.J. "The inertial-response of induction-machine based wind-turbines", *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp.1496 - 1503, Aug. 2005.

[2] Mullane, A., Lightbody, G. and Yacamini, R. "Wind-Turbine Fault Ride- through Enhancement" *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1929 -1937, Nov. 2005.

[3] Lalor, G., Mullane, A., and O'Malley, M.J., "Frequency Control and Wind Turbine Technologies", *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp.1903-1913, Nov. 2005.

[4] Lei, Y., Mullane, A., Lightbody, G. and Yacamini, R. ”Modeling of the Wind Turbine With a Doubly Fed Induction Generator for Grid Integration Studies” I*EEE Transactions on Energy Conversion*, vol. 21, no. 1, pp. 257 - 264, Mar. 2006.

International refereed conference papers

[5] Mullane, A. and O’Malley, ”Modifying the Inertial Response of Power-Converter Based Wind Turbine Generators”, *Proceedings of The 3rd IEE International conference PEMD 2006*, Clontarf Castle, Dublin, Ireland 4 - 6 April 2006

[6] Mullane, A. and O’Malley,”Wind farm models for grid code analysis”, *Proceedings of European Wind Energy Conference*, Athens, February/March, 2006.

[7] Mullane, A., Bryans, G., Lalor, G. and O’Malley, ”Kinetic energy and frequency response comparisons for renewable generation system”, *Proceedings of International Conference on Future Electricity Networks*, Amsterdam, Nov. 2005.

APPENDIX XIII: VTT

Model description
Joint PSCAD/EMTDC and ADAMS model of fixed speed induction generator wind turbine

This annex describes how three commercial programs are used together for continuous and simultaneous simulation of a wind turbine in a power system. A multi-body dynamics code ADAMS is used for modeling the turbine dynamics. The electrical components of the turbine as well as the grid are modeled in PSCAD/EMTDC. Matlab/Simulink is used to combine the simulations.

The described turbine model is a two-speed, passive stall wind turbine with squirrel cage induction generator. The control system is not modeled for this turbine. In this joint modeling environment it is most convenient to model control systems for blade pitching, yawing, generator characteristics etc. in Matlab/Simulink.

ADAMS
The dynamic model of the wind turbine is created using a graphical modeling program ADAMS from MSC Software Corporation. ADAMS is a commercial general-purpose multi-body dynamics code. Wind turbine design is assisted with a special NREL produced package ADAMS/WT [1]. ADAMS models for wind turbines can also be generated with FAST. FAST is a medium-complexity code for aeroelastic analysis of wind turbines developed by NREL [2]. ADAMS/WT has been replaced by FAST and it is not available for purchase any more.

ADAMS models are usually constructed of flexible main components such as blades, tower and drive train. Typically a model consists of a few hundred degrees of freedom. The modeled wind turbine is a Bonus 600 kW Mark IV with arctic equipment (e.g. blade heating). It is a stall regulated two-speed wind turbine, but only the higher rotation speed has been used in simulations. The model contains of three flexible blades, low speed shaft, gearbox, high-speed shaft, generator, flexible tower and nacelle. The blades are divided into ten parts and tower into nine parts. The parts are connected to each other with flexible connections. Because every part has three translational and three rotational degrees of freedom the whole model has about 250 degrees of freedom. Every blade part has two aerodynamic points where the aerodynamical forces are calculated. The drive train model consists of a flexible main shaft, high speed shaft and gearbox. In this turbine model the gearbox contains a planetary stage and two helical stages.

The effect of the wind on the blades is added into the simulation with Aerodyn from NREL [3]. Aerodyn runs as a separate program, which takes blade angles as input from ADAMS and sends calculated output forces back. Aerodyn uses a three-dimensional wind field to calculate the forces created by the wind and the blade profile. The Aerodyn code has been modified by VTT and a new code can use different lift and drag coefficient tables for every blade and the tables can be changed during simulation. The code can now be used to simulate aerodynamical imbalance of an iced rotor, and incidents like ice accretion during wind turbine operation can be studied. There are also improvements for tower shadow model. The original Aerodyn v12.57 code does not calculate the wind speed deficit caused by the tower for upwind turbines.

PSCAD/EMTDC
PSCAD/EMTDC is one of the foremost commercial electromagnetic transient simulation tools. It has been developed by Manitoba Hydro and later Manitoba HVDC Research Center since the 1970’s. The electrical parts of the wind turbine, i.e. generator, capacitor banks and transformer,

and the electrical network, as well as network faults and system disturbances are modeled in PSCAD/EMTDC.

The PSCAD/EMTDC model consists of a standard induction generator model with parameters set to respond the high speed mode of the generator used in the Bonus 600 wind turbine. The capacitor banks and the wind turbine transformer are modeled with standard components with their corresponding parameter values as well.

Matlab/Simulink
In the modeling environment described in this Annex Simulink works as a platform for connecting the electromagnetic simulation to the mechanical simulation.

Simulink is very suitable for modeling complex control systems. With Simulink it is easy to add blade pitch control, yawing, vibration control, generator control and other systems to the dynamic wind turbine model. An additional benefit of using Simulink is that it enables direct use of Matlab.[4]

Combining simulations
The two simulation tools, ADAMS and PSCAD/EMTDC, are communicating during the simulation via Matlab/Simulink. Both ADAMS and PSCAD have their own Simulink interface. ADAMS uses an additional product called ADAMS/Controls from MSC Software. PSCAD/EMTDC standard interface to Simulink does not enable continuous and simultaneous simulation with ADAMS. Therefore new interface modules were developed at VTT for the communication.[5]

The principle of ADAMS-PSCAD simulation is quite simple. Rotation speed information of the generator is transferred from ADAMS to PSCAD. PSCAD calculates electrical counter torque and returns the value to ADAMS. These programs exchange information with a time step of 5 ms. ADAMS runs with variable time step, but it is always smaller than or equal to data exchange time step. PSCAD/EMTDC uses a smaller time step of 50 μs. Data exchange between the simulation programs can be seen in Figure 1.

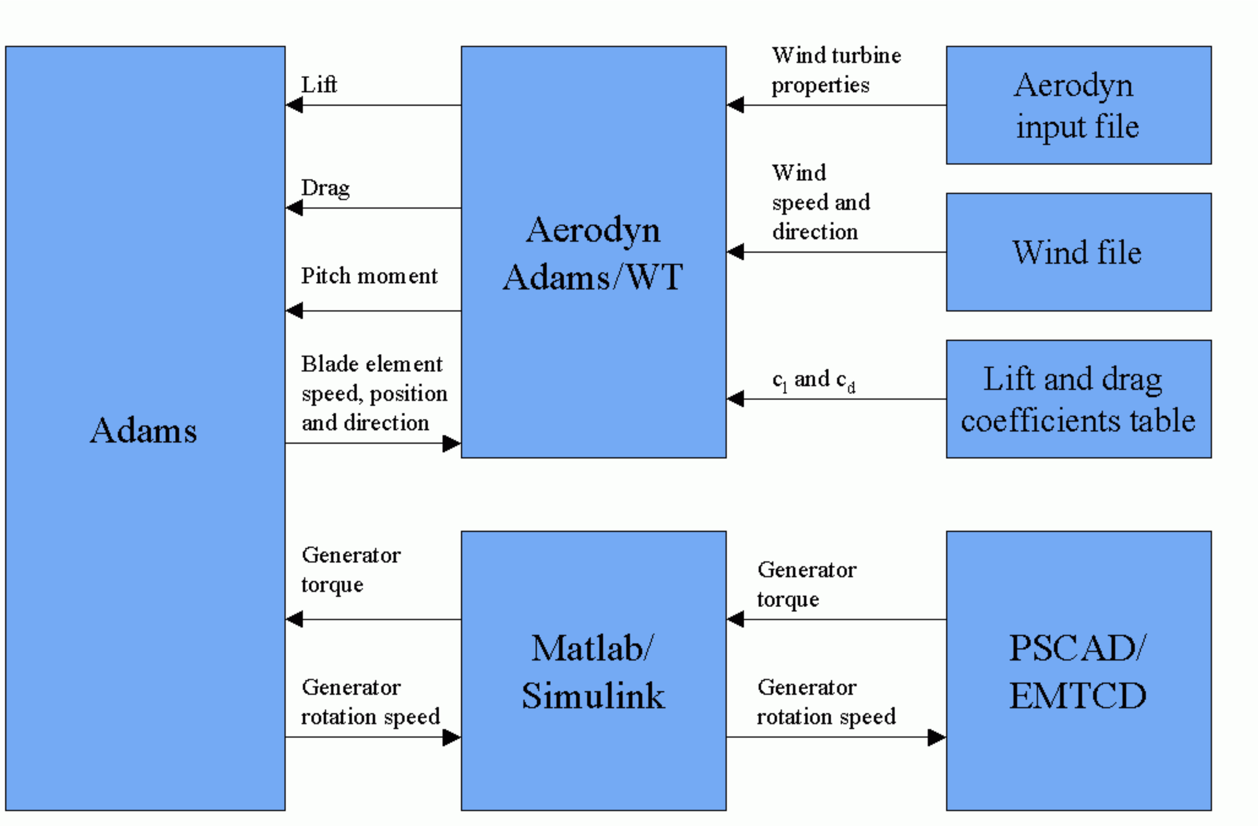


Figure 1. Data exchange between simulation programs.

Comments
Joint simulation with ADAMS, PSCAD/EMTDC and Matlab/Simulink has successfully been conducted by VTT [6], [7].

The greatest use of joint simulation seems to be when one wants to analyse the impact of grid disturbances and faults on the wind turbine and its components. Joint simulation is also useful for developing control and control strategies for wind turbines in case of grid disturbances and for example for fault-ride-through capability. A third practical use is for development of simplified mechanical and aerodynamic models of wind turbines models for power system studies. A verified joint model can be used for comparison when only little measured data is available.
In order to model the mechanical part of a wind turbine in ADAMS a large amount of data describing individual components of the turbine is needed. Model setup in ADAMS is time consuming and not usually worth to do only for power system studies.

Simulations and comparisons by VTT verify that power system studies can often be accurate enough when conducted solely with PSCAD/EMTDC. User defined models (or even standard models) of wind turbine mechanics and aerodynamics are then used instead of the detailed ADAMS wind turbine model. Joint simulation is, however, beneficial when modeling the impact of complex mechanical events on the power system; for example how a mechanical failure or ice accretion on the blades affects the power quality.

Simulink has a power system blockset named SimPowerSystems that can be purchased separately and probably be used instead of PSCAD/EMTDC together with ADAMS. This has however not been tested.

References

[1] http://wind.nrel.gov/designcodes/preprocessors/

[2] http://wind.nrel.gov/designcodes/simulators/fast/

[3] http://wind.nrel.gov/designcodes/simulators/aerodyn/

[4] S. Rissanen, Control of variable speed wind turbine (in Finnish). Master's Thesis, Helsinki University of Technology, Feb. 2004.

[5] J. Kiviluoma, S. Uski, S. Rissanen, B. Lemström, P. Antikainen, E. Peltola, Transient Load and Control Simulation of Wind Turbines Using Simulink, ADAMS and PSCAD/EMTDC, T3SULAWIND project report PRO2/P5107/04. Confidential. VTT Technical Research Centre of Finland, 2004.

[6] S. Uski, B. Lemström, J. Kiviluoma, S. Rissanen, P. Antikainen, Adjoint wind turbine modeling with ADAMS, Simulink and PSCAD/EMTDC, Paper presented at Nordic Wind Power Conference, Göteborg, March 2004.

[7] S. Rissanen & S. Uski. Modelling and Measurements of Dynamic Loads of an Arctic Wind Turbine. Boreas VII Conference, Saariselkä, March 2005.

APPENDIX XIV: LIST OF SELECTED PAPERS BY ANNEX 21

This Appendix list selected papers that have been presented as a joint effort by Annex 21.

Tande JO, E Muljadi, O Carlson, J Pierik, A Estanqueiro, P Sørensen, M O'Malley, A Mullane, O Anaya-Lara, B Lemstrom (2004) "Dynamic models of wind farms for power system studies – status by IEA Wind R&D Annex 21", In proceedings of European Wind Energy Conference (EWEC), 22-25 November 2004, London, UK.

EWEC'06 Session: Dynamic models of wind farms for power system studies - IEA Wind R&D Annex 21; Chairs: John Olav Tande, SINTEF Energy Research, Norway and Mark O'Malley, University College Dublin, Ireland. Papers and presentations are also available at http://www.ewec2006proceedings.info/index2.php?page=searchresult&sess=44%20#top

- BW1.1 DEVELOPMENT AND VALIDATION OF WIND FARM MODELS FOR POWER SYSTEM STUDIES; Jan Pierik, ECN, Netherlands
- BW1.2 ELECTRIC NETWORK FAULTS SEEN BY A WIND FARM – ANALYSIS OF MEASUREMENT DATA; Sanna Uski, VTT Technical Research Centre of Finland, Finland
- BW1.3 MODELLING OF WIND FARM CONTROLLERS; Poul Sørensen, Risoe National Laboratory, Denmark
- BW1.4 COMPARING SINGLE AND MULTIPLE TURBINE REPRESENTATIONS IN A WIND FARM SIMULATION; Brian Parsons, National Wind Technology Center, USA
- BW1.5 WIND FARM MEASUREMENTS AND MODELLING, Kjetil Uhlen, SINTEF Energy Research, Norway
- BW1.6 A WIND PARK DYNAMIC MODEL FOR POWER SYSTEM STUDIES; Ana Estanqueiro, INETI, Portugal
- BW1.7 POWER SYSTEM VOLTAGE STABILITY RELATED TO WIND POWER GENERATION; Ola Carlson, Chalmers University of Technology, Sweden
- BW1.8 ASSESSMENT OF STRUCTURAL DYNAMICS FOR MODEL VALIDATION OF INDUCTION GENERATOR-BASED WIND TURBINES; Anaya-Lara Olimpo, Distributed Generation Research Centre, United Kingdom
- DBW1.9 WIND FARM MODELS FOR GRID CODE ANALYSIS; Alan Mullane, University College Dublin, Ireland

John Olav G Tande, Kjetil Uhlen, Leif Warland, Ola Carlson, Abram Perdana, Jan Pierik, Johan Morren, Ana Estanqueiro, Joao Lameira, Poul Sørensen, Mark O'Malley, Alan Mullane, Olimpo Anaya-Lara, Bettina Lemström, Sanna Uski, Eduard Muljadi, Jarle Eek, Ian Norheim (2008) "Benchmark Test of Dynamic Wind Generation Models for Power System Stability Studies". Submitted to Wind Energy by March 25, 2008.