Dynamic models of wind farms for power system studies – status by IEA Wind R&D Annex 21

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Abstract:

Dynamic models of wind farms for power system studies are at present not a standard feature of many software tools, but are being developed by research institutes, universities and commercial entities. Accurate dynamic wind farm models are critical; hence model validation is a key issue and taken up by IEA Wind R&D Annex 21. This international working group includes participants from nine countries, and has since start-up in 2002 developed a systematic approach for model benchmark testing. This paper present this methodology, including example benchmark test results, but also gives an overview of the various wind farm models now being available from both Annex partners and external entities.
Keywords: wind farms, power system, modelling.

1 Introduction

The worldwide development of wind power installations now includes planning of large-scale wind farms ranging in magnitudes of 100 MW as well as application of wind power to cover a large fraction of the demand in isolated systems. As part of the planning and design of such systems, it is well established that the stability of the electrical power system needs to be studied. The studies are 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 are not standard features. Hence, the user is left to build his or hers own wind farm model. This is not at all trivial and certainly not efficient. Rather a coordinated effort is expected to enhance progress, and consequently Annex 21 under the IEA Wind R&D agreement was started mid 2002 with participants from nine countries.

This paper presents the status of works by the Annex, i.e. including overview of dynamic wind farm models (section 2), measurement database (section 3) and procedure for benchmark testing of models (section 4), and finally example benchmark test results (section 5).

The overview section on dynamic wind farm models gives brief model descriptions, including a summary table of models developed by the Annex participants. 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).

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. In the paper the procedure for this is explained together with example test results. The procedure considers both wind turbine / wind farm operation during normal fault free conditions and response to grid fault.

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 paper.

Symbols used in this paper are listed in the Appendix.

2 Dynamic wind farm models

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 types, but there will also be manufacturer specific variations, i.e. 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.

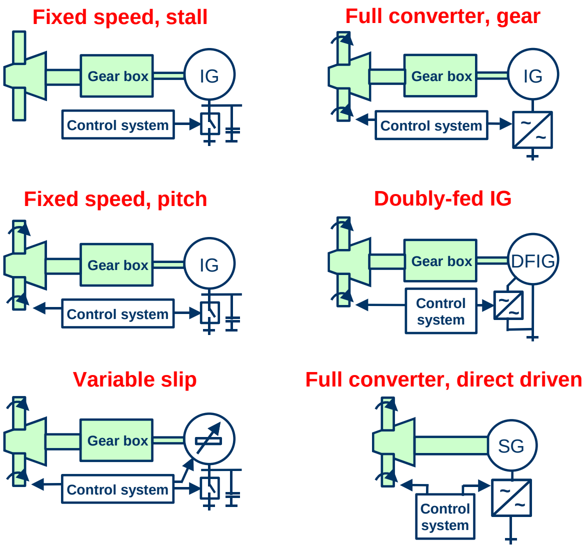

Figure 1: Main types of wind turbine technologies.

Space limitations of this paper does not allow for a detailed presentation of all the various models developed by the participants of the Annex. Hence, in the following only the common building blocks of the models are presented, whereas a brief summary of the models developed by the Annex participants is listed at the end of this section.

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:

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

Here, u_t is the weighted average wind speed over the three rotating turbine blades, i.e. 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:

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

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

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 Annex 21 models

Development of dynamic wind farm / wind turbine models is ongoing amongst the participants of the Annex, see Table 1 (next page) for a brief summary.

3 Measurement database

An important activity of the Annex is the establishment of a database with technical descriptions, simulations and measurement data from wind turbines and wind farms. The data currently 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.
- Azores (Portugal); 4x100 + 1x150 kW wind farm (fixed speed, stall controlled), measurements during normal operation.
- DFIG850 (Sweden); 850 kW DFIG wind turbine, measured 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 dips.

The present dataset provides a fair basis for testing benchmark procedures, but should be expanded with data and measurements to constitute a better basis for model validation. Firmly planned new data to be added are from a 70 MW wind farm in Donegal, Ireland, with fixed speed, "grid code compliant" wind turbines (Bonus with thyristor switched capacitors; measurements are prepared by University College Dublin to be ongoing before end 2004). Further work is still in progress on collecting measurements from variable speed wind turbines, and during transient events, e.g. voltage dips. VTT, ECN/TUD and Chalmers are all active in pursuing such data collection.

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

4 Benchmark test procedure

A first set of benchmark test procedures have been developed. The proposal so far is as outlined in this section.

The test should be kept simple, i.e. to start with considering only the following results:

Dynamic operation during normal conditions:
- 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 vs voltage and reactive power vs active power

Response to voltage dip:
- Input:
  - Voltage time series and constant aerodynamic torque (or optionally wind speed time series)
- Output:
  - Time series plot of active and reactive power output
  - Time series of voltage at wind turbine terminals

The benchmark test may include both validation against measurements and model-to-model comparisons.

Measurement data from a 180 kW fixed speed, stall controlled wind turbine and an 850 kW DFIG wind turbine are now used as a first case for testing the proposed benchmark procedure.

Partner	Tool	Model	Type	Validated	Comment
Chalmers	Matlab PSSE DigSilent	Fixed speed DFIG Direct Drive Fixed speed Fixed speed DFIG	Dynamic/Transient Dynamic/Transient Dynamic/Transient Dynamic/Transient Dynamic/Transient Dynamic/Transient	Yes/Yes Yes/Yes (Yes/Yes)[1] Yes/Yes Yes/Yes No/No	Models and study reported, see [1] and at http://www.elteknik.chalmers.se/ [1]Converter validated in lab.
ECN/TUD	Matlab	Fixed speed DFIG Direct Drive Full Converter[2]	Dynamic/Transient Dynamic/Transient Dynamic/Transient Dynamic/Transient	No/No No/No No/No No/No	Models and study reported, see [2]-[3] [2]Model include cluster control of multiple induction machine wind turbines connected to one common frequency converter
INETI	INPark INDUSAT Matlab	Fixed speed Direct Drive WP Aggregate Fixed speed Direct Drive	Dynamic/Transient[3] Dynamic/(Transient) Dynamic/Transient[4] Dynamic/Transient Dynamic/(Transient)	Yes/Yes No/No Yes/Yes Yes/No No/No	[3]INPark model was developed by INETI for grid integration assessment. LIB modular routines available by request. Models and study reported, see [4]-[6]. [4]Wind park aggregate models are developed by UTL – Technical University of Lisbon being under revision by UTL/INETI for actual technologies, see [7].
NREL	PSSE RPM-Sim	Fixed speed[5] DFIG[6] Fixed-Speed[6] Var Slip[6] Full Converter[6] Fixed speed[7]	Dynamic/Transient (Dynamic)[8]/Transient (Dynamic)[8]/Transient (Dynamic)[8]/Transient (Dynamic)[8]/Transient Dynamic/(Transient)	Yes/No No/No No/No No/No No/No Yes/No	Models and study reported, see [8]-[9]. [5]PSSE model developed by NREL in cooperation with Southern California Edison [6]PSSE models (manufacturer specific) developed for ERCOT by PTI, tested by NREL [7]RPM-Sim is a stand alone model for simulation of wind turbines and hybrid systems. The RPM-Sim models are available at wind.nrel.gov/designcodes/simulators/rpmsim/ [8]Wind field is modeled by aggregation.
Risø/AAU	DigSilent Matlab	Fixed speed DFIG Fixed speed DFIG	Dynamic/Transient Dynamic/(Transient)[8] Dynamic/Transient Dynamic/(Transient)[9]	Yes/Yes No/No Yes/No No/No	Models and study reported, see [10]-[11]. Matlab model library available at www.iet.aau.dk/Research/wts.htm www.iet.aau.dk/Research/spp.htm [8,9]DFIG model to be expanded with crow bar
SINTEF	PSSE Matlab SIMPOW PSCAD[12]	Fixed speed DFIG Direct Drive Fixed speed DFIG Direct Drive Fixed speed -	Dynamic/Transient Dynamic/(Transient)[10] Dynamic/Transient Dynamic/Transient Dynamic/(Transient)[11] Dynamic/Transient Dynamic/Transient -	Yes/Yes No/No No/No Yes/Yes No/No No/No Yes/Yes -	Models and study reported, see [12]-[14]. [10,11]DFIG model to be expanded with crow bar [12]PSCAD is used for detailed studies of power electronics' impact on power system stability
UCD	Matlab PSS/E	Fixed speed DFIG Full Converter	Dynamic/(Transient) Dynamic/(Transient) Dynamic/(Transient)	No/No No/No No/No	Models and study reported, see [15].
UMIST	Matlab PSCAD	Fixed speed[13] DFIG[13] DFIG[14]	Dynamic/Transient Dynamic/Transient Dynamic/Transient	No/No No/No No/No	Models and study reported, see [16]-[18]. DFIG models available at www.dgsee.umist.ac.uk/dfig/index.html [13]3rd and 5th order models [14]5th order model
VTT	ADAMS[15] Matlab[15] PSCAD[15]	Fixed speed	Dynamic/Transient	No/No	Models and study reported, see [19]. [15]ADAMS and PSCAD-models are run jointly by Matlab

Table 1: Summary of models developed by the participants of IEA Wind R&D Annex 21.

5 Example test results

5.1 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. Results are shown for normal operation, Fig 2-3, and for the event of a voltage dip, Fig 4-5. The applied wind turbine data are given in the Appendix.

The time-series plot of active power output, Fig 2, 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.

The power spectral density (PSD) plot of active power output, Fig 3, 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). The employed model makes a fair fit, but misses the 1p fluctuation as rotor blade unbalance is not included in the model.

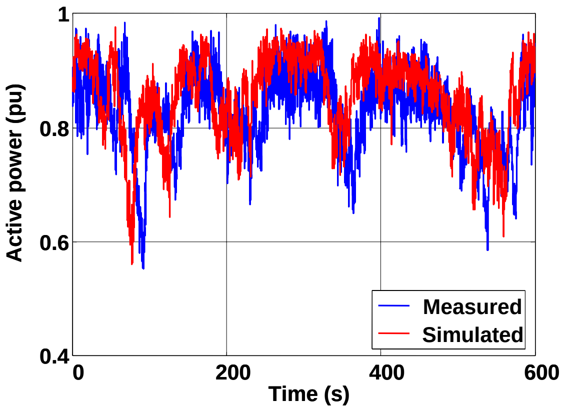

Figure 2: Measured and simulated active power output from fixed speed, stall controlled wind turbine.

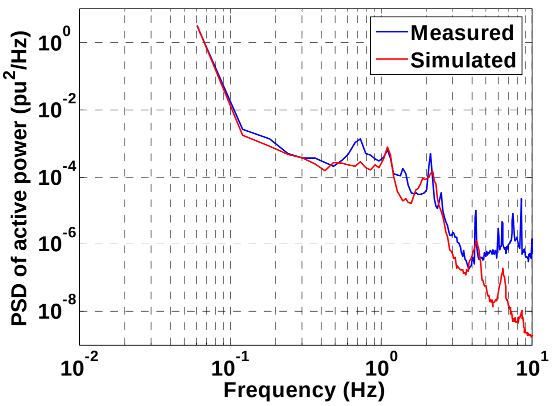

Figure 3: Power spectral density (PSD) of measured and simulated active power output from fixed speed, stall controlled wind turbine.

The wind turbine response in active power output to the voltage dip, Fig 4-5, is significant. The frequency of the simulated response matches the measured fluctuation (~10 Hz), but the measured power fluctuation amplitude is somewhat higher than the simulated. The match in frequency indicates that the model is fair, but more accurate simulation of the voltage dip and/or more detailed generator (stator) representation must be applied for better match in fluctuation amplitude.

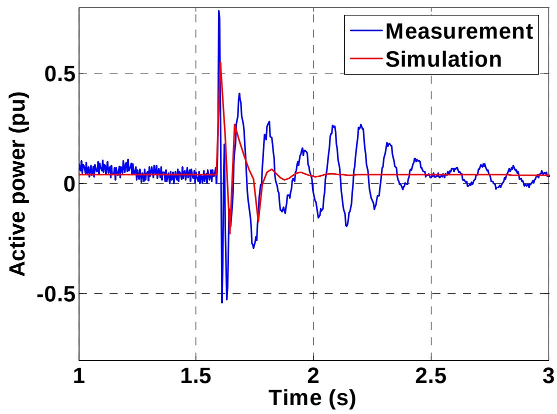

Figure 4: Time-series of measured and simulated active power output from fixed speed, stall controlled wind turbine during voltage dip.

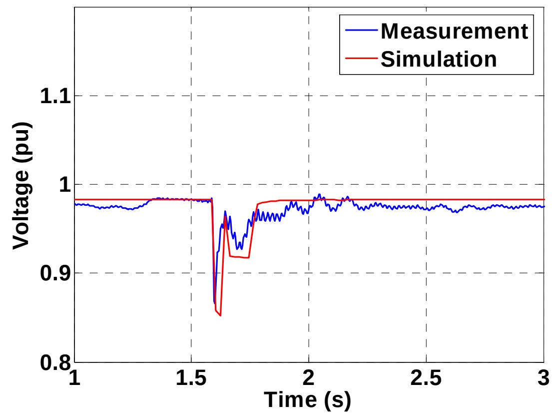

Figure 5: Time-series of measured and simulated voltage dip at wind turbine terminals.

5.2 Variable speed wind turbine

In this section example test results are presented comparing measurements and simulations of a 850 kW DFIG wind turbine. Results are shown for the event of a voltage dip, Fig 6-7. The applied wind turbine data are given in the Appendix.

The simulated response in active power output of the wind turbine to the voltage dip, Fig 6-7, reflects the measured response, but not accurately. The main challenge is that the response is to a large degree governed by the control system of the wind turbine, and that this is not known in detail.

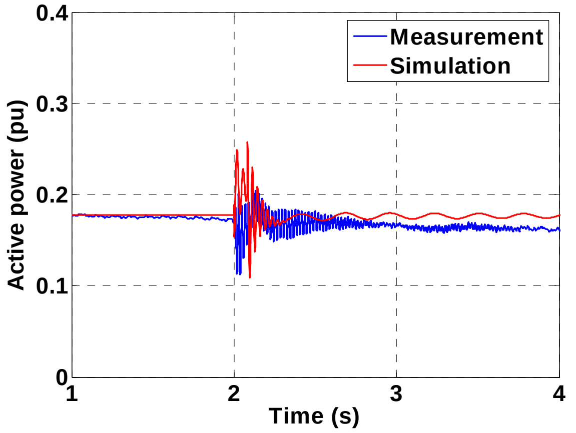

Figure 6: Time-series of measured and simulated active power output from variable speed DFIG wind turbine during voltage dip.

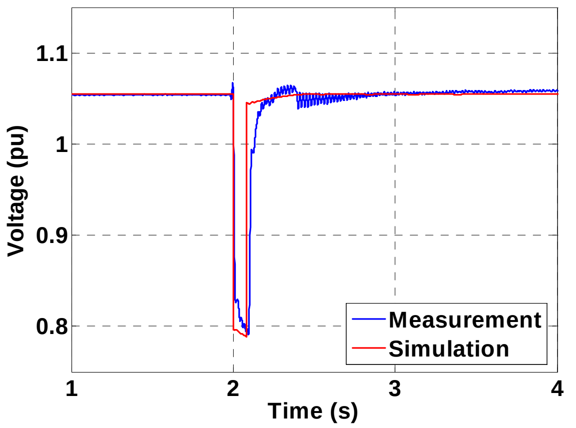

Figure 7: Time-series of measured and simulated voltage dip at wind turbine terminals.

6 Conclusion

In general the progress is good on model development. Models are available on various platforms (Matlab, PSSE etc), some are freely available, and the Annex participants take model validation seriously providing confidence.

The common major challenge is seemingly to validate the response of models on grid faults such as severe voltage dips. Relevant measurements are not easy to obtain and a further difficulty is that the response is very dependent on the detailed control of the wind turbine(s), i.e. specifications that are commonly regarded as a business secret by the manufactures. Hence, a proposal emerging as a spin-off from the Annex works is to update IEC 61400-21 to specify standardized procedures for measurements and documentation of the response of wind turbines on voltage dips, and by this lay the foundation for model validations. This work has now started aiming to prepare a draft revision of IEC 61400-21 by June 2005.

This paper has described the status of works by IEA Wind R&D Annex 21. The work is ongoing, planned to being concluded by end 2005, and by then a more elaborate presentation of models and benchmark test results are expected.

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Appendix

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)

Data conversion formulas

$$Z_b = \frac{U_n^2}{S_n} \tag{4}$$

$$\omega_b = 2\pi f_n \tag{5}$$

$$H_t = \frac{0.5 J_t \omega_b^2}{S_n n_g^2 p^2} \tag{6}$$

$$H_g = \frac{0.5 J_g \omega_b^2}{S_n p^2} \tag{7}$$

$$\omega_o = 2\pi f_o \tag{8}$$

$$k = \frac{2\omega_o^2 H_t}{\omega_b} \tag{9}$$

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)	0.017
Stator leakage reactance, X_{1S} (pu)	0.105
Rotor resistance, R_{2S} (pu)	0.015
Rotor leakage reactance, X_{2S} (pu)	0.107
Magnetizing reactance, X_M (pu)	3.188
Shunt-capacitor, Q_c (kvar)	60
Generator inertia, H_g (s)	0.28
Turbine inertia, H_t (s)	3.14
Mechanical drive train eigenfreq, f_0 (Hz)	0.81
Gearbox ratio, n_g	23.75
Turbine rotor radius, R (m)	11.60

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)	0.004
Stator leakage reactance, X_{1S} (pu)	0.046
Rotor resistance, R_{2S} (pu)	0.006
Rotor leakage reactance, X_{2S} (pu)	0.072
Magnetizing reactance, X_M (pu)	2.724
Frequency converter rating, S_f (kvar)	300
Generator inertia, H_g (s)	-
Turbine inertia, H_t (s)	5.23
Mechanical drive train eigenfreq, f_0 (Hz)	-
Gearbox ratio, n_g	57.69
Turbine rotor radius, R (m)	26.00