RESEARCH REPORT

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Wind turbine models – Status report of model development and verification measurements

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Summary

Today there seems to be more commonly wind turbine models available for different simulation software as part of the simulation software model libraries. The generic models representing the four common wind turbine technology types appear to be more attractive than need of creating the models from the scratch for individual wind turbines for specific simulation purpose. Using generic models could be advantageous to all parties involved.

This report reviews a selection of different electrical simulation software as well as wind turbine models available in some different simulation software, PSS/E, DIgSILENT and PSCAD/EMTDC.

Based on this report, the PSS/E generic models and PSCAD/EMTDC DFIG model will be tested, assessed and analysed in the following phase of the SGEM-project. There is also measurement data available of a full power converter equipped wind turbine that can be used for model validation and parameterization.

Confidentiality	Public

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Contents

1 Introduction

The SGEM-project subtask 5.1.1 “Network integration of distributed generation” contains a work task developing further the existing wind turbine and wind farm models for simulations of distributed generation, as well as model assessment in validation purpose. This work is done during the second and third year of SGEM-project. This report describes the work done during the second year in SGEM-project, and consists of review of existing, publicly or easily available models, and model validation data. The model review is limited to publicly and widely available models due to the fact that it is recognized that it would be beneficial for all parties to use similar or same generic models within possibilities.

There are several different simulation software products for electrical system and power production simulations. Some of these simulation tools have similar qualities and are developed and delivered by different companies, but on the other hand, different software may have separate modelling and simulation precision, and they serve (best) different purposes. Therefore, the most common simulation tools for electrical systems and components are first introduced in chapter 2. The general background of wind turbine modelling is glanced in chapter 3. In the following chapters 4-6 existing wind turbine and wind farm models for some relevant simulation software are reviewed. Chapter 7 deals with wind turbine model validation data.

2 Simulation software review

Simulation imitates the real phenomena, and a (computer) simulation model is a mathematical model, e.g. set of equations, representing the actual device operation and reactions under simulated situations. Typically the electrical simulations are carried out in time-domain. There are simulation tools for different purposes in electrical engineering, e.g. looking at the power system level phenomena, or on the other hand looking at the electrical machine detailed operation and phenomena. The level of simulation precision and simulation time-steps vary in these different simulation tools for different purposes, and they require different level of modelling as well. Approximation of different electrical system phenomena time-frames are shown in Figure 1.

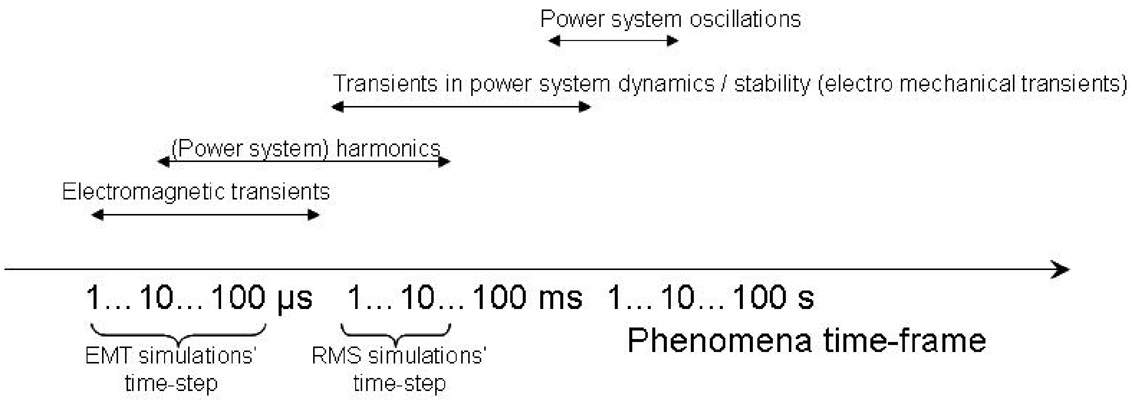


Figure 1. Time-frame of different phenomena to be considered in modelling precision and simulation set up of electrical phenomena.

Some of the commonly used simulation software products are:

- **PSCAD/EMTDC** – electromagnetic transients time domain simulation software for electrical (both electromagnetic and electromechanical systems) and control systems, *commercial software*
- **ATP-EMTP** – electromagnetic transients time domain simulation software for electrical (both electromagnetic and electromechanical systems) and control systems, *free of charge licensed software*
- **PSS/E** – electrical transmission system simulation software, *commercial software*
- **DIgSILENT PowerFactory** – power system analysis tool e.g. for applications in power transmission, distribution, and generation, *commercial software*
- **SIMPOW –** power system simulation software, focusing mainly on dynamic simulation in time domain and analysis in frequency domain, *commercial software*
- **Matlab Simulink -** an environment for multidomain simulation and Model-Based Design for dynamic and embedded systems, contains e.g. additional toolbox SimPowerSystems for modelling and simulation of the generation, transmission, distribution and consumption of electrical power, *commercial software*

The performance of different commercial simulation tools, PSCAD/EMTDC, PowerFactory, SIMPOW and PSS/E were compared in [1] related to fixed speed wind turbine model response to a grid fault (symmetrical and unsymmetrical fault). Although some of the software compared are mainly targeted for different simulation tasks, especially PSS/E and PSCAD/EMTDC, the paper [1] shows that different simulation software give rather accurate simulation results compared to each other within their simulation task repertoire. The paper also gives a good idea of what kind of results and in what precision – e.g. electromagnetic transients or just RMS (root mean square) values – different simulation tool results are. For those pursuing to start running simulations, correct selection of the simulation software – and the simulation precision – is the first and important task to do. In none of the tested software in [1], there was used a standard wind turbine model provided with the software, but the wind turbine model was implemented using standard component models (i.e. generator model etc.) and user defined components in case no suitable standard component was available.

3 Wind turbine modelling background

There is work going on around standard IEC 61400-27 for ”Electrical simulation models for wind power generation”, which will define the generic simulation models for wind turbines and wind power plants [2]. The standard deals with the dynamic models to be used for power system stability simulations. It specifies the level of modelling detail, and which features the different wind turbine type generic models will need to have. The standard presupposes model validation to be based on measurements described in IEC 61400-21.

In addition, the IEEE and WECC working groups are studying wind turbine model issues and recommend the path towards the generic models [3,4].

4 PSS/E

PSS/E is power system simulation software, used mainly in the transmission system simulations (see Table 1 for specifics), and thus generally excluding distributed generation. Although generally used for high voltage transmission system modelling, PSS/E can be used also for lower voltage level, and smaller scale power system simulations. E.g. in case of small power systems, the small scale power production and distributed generation can be relevant to be modelled. Practically there are no limitations on power production unit size to be modelled in PSS/E, i.e. individual wind turbines may be modelled in PSS/E. There are generic wind turbine models for different turbine types provided along with the current PSS/E software revision 33 (in certain extent these generic wind turbine models have been provided since revision 31). In addition there are manufacturer specific wind turbine models that may be downloaded or requested upon need (Table 2). Related to distributed generation, in addition to the wind turbine models, there is a generic model for photovoltaic (PV) plant connected to the grid via power converter provided with PSS/E.

Table 1. PSS/E simulation features and capabilities. [5]

Steady State	Time Domain	Frequency Domain	Advanced Modules	Data Management and Program Interfaces
Power flow	Dynamics	NEVA**	Optimal power flow (OPF)	PSS®E integration with Google Earth
Short circuit ANSI, IEC	Vast library of machines models, load, FACTS device, DC lines, generic wind turbines	Eigenvalue/modal analysis	Graphical Model Builder (GMB)**	PSS®ODMS enterprise wide Network model management
Probabilistic and deterministic contingency analysis	User developed models		Protection*	MOD® Web-based planning project case manager
Multi-level contingency analysis D N-1 / N-2 / N-3	Manufacturer specific wind-turbine models		Distance protection	PSS®MUST Managing and Utilizing System Transmission
PV/QV analysis	Integrated plotting package		Overcurrent time protection	PSS®DB integration platform for PSS® software
Non-divergent power flow			Protection simulation	
Spread sheet interface, slider diagram			Harmonics*	
Python scripting				
Vast array of APIs, automation capability via IDEV, Python, IPLAN, PSAS, PSEB				
Contour plotting				
Scenario manager				

* PSS®SINCAL Module
** Module shared by other PSS® products.

There are all common wind turbine types covered by the PSS/E generic wind turbine models to be used in studies related to integration of wind turbine generators in electrical power systems [6, 7];

- Type 1. Direct connected Conventional Induction Generator
- Type 2. Wound Rotor Induction Generator with Variable Rotor Resistance
- Type 3. Doubly-Fed Induction Generator (DFIG)
- Type 4. Full Size Converter Unit (including a generator as well)

There is some publicly available information on the models in [7], and more thorough and up-to-date information in PSS/E software manuals [6].

These generic wind turbine models are not developed to be accurate in studies with frequency excursion, nor to reproduce advanced power management features, e.g. programmed inertia and capability of spilling wind [6]. Related to distributed generation simulation studies, the models omitting the frequency excursion response rules out island operation studies, and sets limitations for studies related to small power systems (in which the frequency excursions could be an integral phenomenon).

Table 2. Wind turbine manufacturer specific wind turbine models for PSS/E downloadable for PSS/E users. [8, 9]

PSS®E Wind Package Information

Latest Revision October 13 , 2011

Click to view change log.

Modifications:

Click here to download Protection User Guide.

Manufacturer	**Wind Packages for PSS®E Versions 29 and Later**	**Package Download**
Acciona AW15/30	psse_aw1530_w500.exe	Click here to request to download the package.
Enercon ExF2	psse_EnerconExF2_w1.exe	Click here to request to download the package.
Fuhrlaender FL2500	psse_fl2500_w403.exe	Click here to request to download the package.
GE 1.5/1.6/2.5/2.75/4.0 MW	psse_gewt_w600.exe	Click here to request to download the package.
Generic WT3	psse_wt3_w402.exe	Click here to request to download the package.
Mitsubishi MPS-1000A	psse_mps1000a_w5.exe	Click here to request to download the package.
Mitsubishi MWT-92/95/100/102	psse_ mwt_w600.exe	Click here to request to download the package.
Siemens WT4	psse_siemensWT4_w1.exe	Click here to request to download the package.
Vestas V80/V47	psse_v8047_w410.exe	Click here to request to download the package.
Vestas V82	psse_v82_w41.exe	Click here to request to download the package.

The generic PSS/E models delivered with PSS/E consist of several model components, e.g. the generator model, rotor resistance control model, converter control model, wind turbine model, pseudo governor model (deals with the aerodynamic phenomena/influence), and pitch control model [7]. There are different and specific component models for each wind turbine generator type and some of component models may be used for two different wind turbine types (e.g. same turbine model for types 1 and 2). For some component models there are two component models to choose from (e.g. different generator models for type 4). The generic models are given example/default data and parameters, and the component model control diagrams are given and explained so that the user may specify the parameters differently as well. There are no validation description/reporting available for the models and/or example data, which in many cases is given as reference to a certain wind turbine, e.g. type 3 to GE 1.5 MW wind turbine, type 4 to GE 2.5 MW and Siemens 2.3 MW wind turbines.

These generic models will be tested in the following phase of the SGEM-project task in order to

- assess the provided example/default parameters (i.e. the minimum effort to apply the models in simulations)
- assess the model parameterization (i.e. applicability of the models for specific wind turbine and its control), and how comprehensive, unambiguous and easy to provide the parameters are (i.e. in case parameters to be provided by the turbine manufacturer/owner/operator)
- assess in which level of complexity specific wind turbines are necessary to be modelled for certain simulation purposes, e.g. if it is necessary to include also the aerodynamic model (i.e. pseudo governor model) or the pitch control model and in case some of the features could be omitted in some cases, and what kind of influence this would have in the overall wind turbine model accuracy under different simulation circumstances.

5 DIgSILENT PowerFactory

DIgSILENT PowerFactory[1] is widely used simulation software. It is capable of simulating from short term transient stability to long term control design situations and it is used in transmission and distribution networks, industry, wind farms, PV systems and smart grids. DIgSILENT software has public educational materials in web [10, 11, 12, 13] and Risø Technical University of Denmark has made full scale report of software features [16]. In software manual is mentioned for example induction machine, DFIG, synchronous machine and PWM (pulse-width modulated converter) module for converter connections for wind turbine simulations. DIgSILENT operating environment and software characteristics are listed below [14]:

[1] PowerFactory is the name of the software provided by DIgSILENT GmbH, but the software is widely called also by only the company name as “DIgSILENT” as well as “PowerFactory”.

- Different PowerFactory applications
    - Transmission and distribution
    - Industry
    - Wind power and PV systems
    - Smart grids
- Generic wind turbine models with Generator models (squirrel cage, double-fed, direct driven)
- Manufacturer-specific high-precision wind turbine models are available upon request
- Enhanced features (rectifier and inverter models, PWM converter, etc.)
- Stability analysis and electromagnetic transients (EMT)
- Wind farms, verification, control design, harmonic penetration, voltage stability, fault recovery
- Libraries
    - Equipment types (wind turbines etc.)
    - Operation information
    - DIgSILENT programming language (DPL script)
    - Templates
    - User-defined models

According to DIgSILENT [15], for PowerFactory Version 14.1 there is a new global "Templates" library made available that contains "ready for use" models of

- Double Fed Induction Wind Turbine Generator (0.69 kV) and
- Fully Rated Converter Wind Turbine Generator (0.4 kV)

for unit sizes of 1.0 MW, 1.5 MW, 2.0 MW, 2.3 MW, 2.5 MW, 2.7 MW, 3.6 MW, 5.0 MW, 6.0 MW, as well as

- Variable Rotor Resistance Wind Turbine Generator (0.69 kV) for a 0.66 MW unit.

In addition to these wind turbine models and related to distributed generation, there is a template model for photovoltaic (PV) plant of 0.5 MVA at 0.4 kV, as well as a 30 MVA battery system model with frequency converter for 10 kV. [15]

DIgSILENT software and wind turbine models are studied and reported in Risø report by Hansen et al. [16]. This second edition report was published in year 2007 and it is based on several Danish national research projects in the period 2001-2007. Further studies with DIgSILENT built-in wind turbine generator models are done for example in Master theses by Hamon [17] and Sada [18].

In DIgSILENT software there are two built-in DFIG models. Hamon has made some detailed and well documented comparison of these two models as well as a user-built model [17]. A PowerFactory built-in DFIG wind turbine model has two hierarchical control levels (see Appendix B): DFIG vector control (electrical fast control) and wind turbine control (slow control). In normal operation turbine is used in optimal operation point and power production is limited to nominal production P_{gen}. Rotor-side converter controls active power P and reactive power Q between wind turbine and grid connection point. Grid-side converter controls DC voltage of the voltage source converter (VSC) and operates the rotor circuit on unity power factor. The DFIG fault ride-through (FRT) feature can be implemented in case needed. FRT operation module is implemented as an extension of control structure. [16]

The permanent magnet synchronous generator (PMSG) model implemented in [16] contains aerodynamic rotor model and pitch angle control, and has full power converter and two-mass drive train model. This PMSG model does not have damping windings and drive train is modelled as soft between aerodynamic rotor and multipole generator. [16]

6 PSCAD/EMTDC models

PSCAD/EMTDC is an electromagnetic transients time domain simulation software for electrical and control systems. It is one of the first real time digital simulation software products for power systems and it has been developed over two decades from year 1991. Today PSCAD library contains examples and ready-to-use models for wind turbine simulations (e.g. in PSCAD*/EMTDC program files in …\PSCAD42\examples\WindFarm).

Basic wind turbine model is a simple induction machine without any converters. There are two example case models of this type in PSCAD, *windfarm_indmac.psc* and *wind_gensoftstart.psc*. In Figure 2 is Wind farm- induction machine with soft starter (of *wind_gensoftstart.psc*) and T_{wind} is an input parameter e.g. as output simulated by MOD 2 type mechanical turbine component model (called as wind turbine model, see Figure 3).

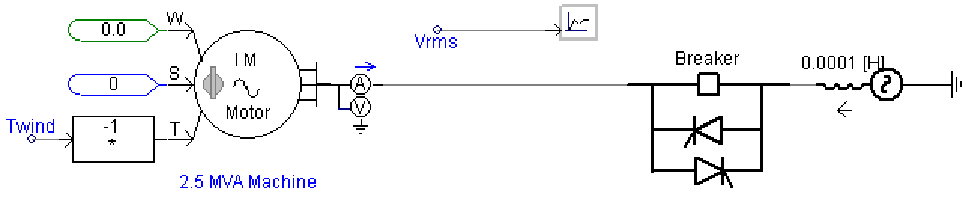


Figure 2. Induction machine with wind turbine model input. [19]

Wind turbine mechanical model (*MOD 2 type*) can use *Wind source* component to specify properties of wind speed, e.g. wind speed mean value, gust, ramp and noise. *Wind turbine governor* is a pitch angle controller and it uses mechanical speed and power output of the machine as inputs. The mechanics (e.g. the turbine masses and shaft properties) are not included in the model. The MOD 2 type wind turbine component is based on rather old academic publications on wind turbines from early 80's, and the models correct operation was questioned in [20].

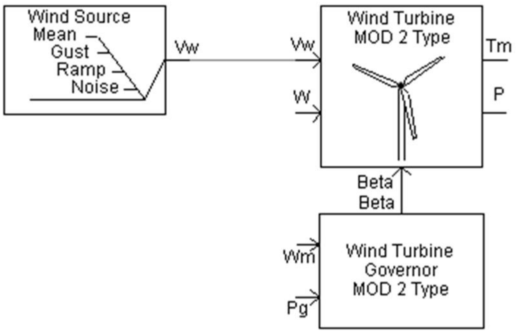


Figure 3. MOD 2 type Wind turbine model. [19]

PSCAD example *windfarm_synmc.psc* synchronous machine in Figure 4 is built with generic library components and machine shaft torque T_m is as an input from *MOD 2* wind turbine component. This synchronous machine model does not include power converter, which would be needed if simulations of full power converter equipped with synchronous machine would be of interest to study. Therefore the example model itself is not quite applicable "as is" for wind turbine electrical simulations.

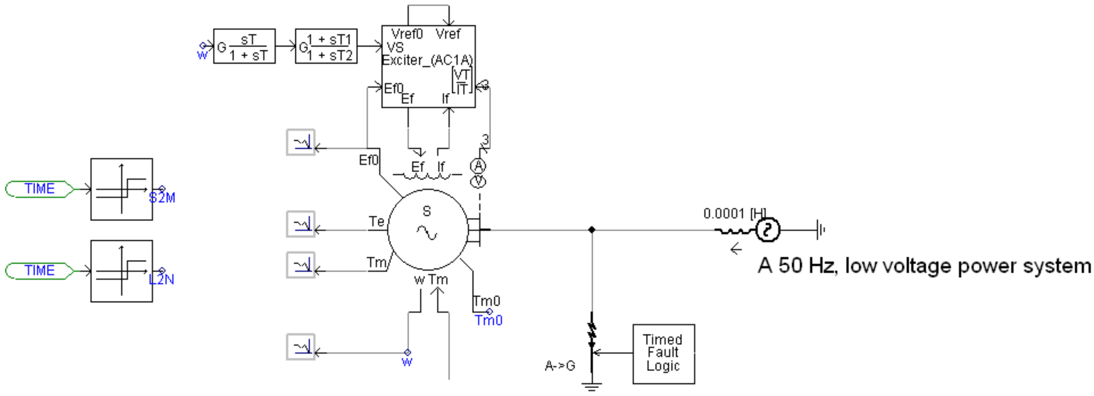


Figure 4. Synchronous machine with wind turbine model input. [19]

Modified *DFIG_V4_November_2010* wind turbine model in Figure 5 is an additional model and it can be downloaded from webpage of PSCAD software [21]. The model documentation supposed to be attached to this model download does not follow with the model package for some reason, but is available from Manitoba HVDC upon request. According to the documentation the DFIG model controller concept is based on [22]. The documentation does not mention if the model has been validated. The downloadable model version seems to contain some minor bugs that need to be corrected before it can be even run (e.g. variable names). It is a full scale model with rotor circuit converter and crowbar protection. The model represents a single 2 MW DFIG wind turbine initially (although the "Wind park" component in the model might imply otherwise). This DFIG wind turbine model will be tested and analysed further in the next phase of the SGEM-project task.

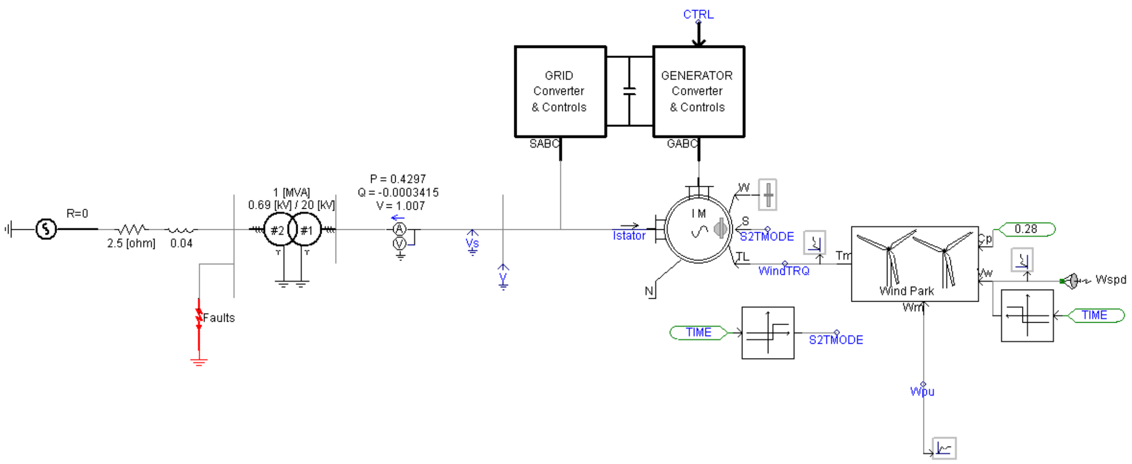


Figure 5. Modified PSCAD-model "Wind farm, vector controlled doubly-fed induction generator" in package DFIG_V4_November_2010. [21]

Some extensive or further reporting of wind turbine simulations with PSCAD/EMTDC can be found e.g. in [23, 24].

The wind turbine generator models and other PSCAD models which relate somehow to wind turbine generators and SGEM research program are acknowledged as well in this report. Finnish universities have studied distribution grid issues and wind turbine connections in small scale using mostly induction machines as generators. These models are presented in a list Appendix A by model owner or developer. Also reports of certain models are listed in same Appendix A. To notify couple of the reports VTT Olos-pilot_V2 and Högsåra report 2003 are made to study distribution network operation with some fixed speed wind turbines connected to the grid. All the wind turbine models are at least partly user specified and for future it is necessary to have generic wind turbine models as specified in standard IEC 61400-27 [2]. It is not necessary to review the fixed speed wind turbine models in detail because this turbine type is not likely the one to be used in new installations. In addition the fixed speed wind turbine models are fairly simple to implement and are rather well validated.

7 Wind turbine and farm model validation data

For fixed speed wind turbines there is more measurement data available, e.g. VTT has been involved in carrying out disturbance measurements at Olos wind farm, as well as has access to some other similar measurement data from different locations and wind turbines. These data are commonly measurements of voltage dip(s) in the grid, where the phase voltages and currents of the wind turbine are measured at different sampling frequencies. The data usually contains a short period of pre-fault situation, and continues after a short period after the fault (e.g. a few seconds) so that the wind turbine response to the grid fault is seen. [25, 26, 27] These data has been used for validation of fixed speed wind turbine models, e.g. [28, 29, 30].

VTT has carried out disturbance measurements with ABB in a small wind farm consisting of full power converter equipped wind turbines [31]. The measurements were done to be triggered of disturbance situations in the grid, i.e. voltage dips. Measurements were done and triggered separately of a single wind turbine and the whole wind farm. The phase voltages and phase currents were measured at 2 kHz sampling for 3.5 second measurement period with 0.5 s of pre-triggering data. This measurement data could be used for validation of the full power converter equipped wind turbine models, and identification of generic model parameters for one wind turbine (certain manufacturer and model). It could be used also for assessment of the correspondence of the turbine common parameters vs. generic model parameterizing features, as well as the parameterized generic model operation/response in fault situation comparison to disturbance measurements of actual operation under fault incident.

8 Conclusions and further work

8.1 Conclusions

Today there seems to be more commonly wind turbine models available for different simulation software as part of the simulation software model libraries. The generic models – four dedicated generic models representing each of the different four commonly categorized wind turbine technology types – seem to be more attractive than need of creating the model from scratch for each different wind turbine (specific by manufacturer and turbine type, size, technology solutions etc.). Even the IEC 61400-27 standard under preparation focuses on the generic models. The transmission grid or distribution network operator may require the model of a specific wind turbine in their grid for different simulation software. Especially for power system simulations it would be easier for turbine owners/operators/manufactures to provide only the parameters for a generic model of the wind turbine instead of being obliged to build and provide a whole model. For grid/network owners using the same generic models, it would be an advantage to compare different wind turbines and their performances when using the same models only with characteristic parameters – as is often the case with conventional power production units – and the models would not be any more as black-box type as possibly would be with manufacturer provided models with their individual tricks and procedures needed in running the simulations. In addition the generic model itself, as well as along with experience on using these models, the influence of different parameters and their values will become better known. This may contribute in developing e.g. the requirements to be set for wind turbines, as well as help identifying the possibilities of utilising wind turbines to help the power system (e.g. identifying that certain parameter change by certain magnitude could improve the power system reliability in such-and-such extent).

8.2 Further work

This report is part of the work done under topic “Wind power grid connection, models and modelling” and the attempt to identify the wind turbine modelling status as preliminary information on proceeding and completing the task. In further work the PSS/E generic models will be tested, assessed and analysed. In addition the available PSCAD models, specifically the DFIG wind turbine model, will be tested and assessed.

The measurement data mentioned in chapter 7 can be used for validation of the models and model parameterization for specific wind turbines.

The tested models with either default generic model parameters or the models parameterized for specific wind turbines, will be used for analysing wind power impacts on regional networks e.g. taking as input the work done so far on how to manage fault location and protection when generation in distribution networks. In addition, according to the study plan the wind farm internal system design and applicability of various auxiliary elements (capacitors, SVC, reactors etc.) will be evaluated in order to be able to fulfil the requirements from the grid side (e.g. fault ride-trough).

Appendix A: List of PSCAD component model libraries

List of component model libraries related to wind turbines:

- HElib
  - Production unit models
    - DFIG_2MW_1_0, year 2005
    - DFIG_crowbar_1_0, year 2007
    - PM_300kVA_tuulim2, year 2006
    - DTC_drive_v1, year 2006
    - Wind_1x65_01, year 2004
    - Wind_2x30_01, year 2004
    - olos-pilot_V1, year 2006
    - FINkjavo_tuulipuisto, year 2007
    - FINkjavoPJK, year 2007
    - FINkjavoPJKSL, year 2007
- TUT
  - Hailuoto
  - Högsåra
- Switch
  - Full converter model, 2011

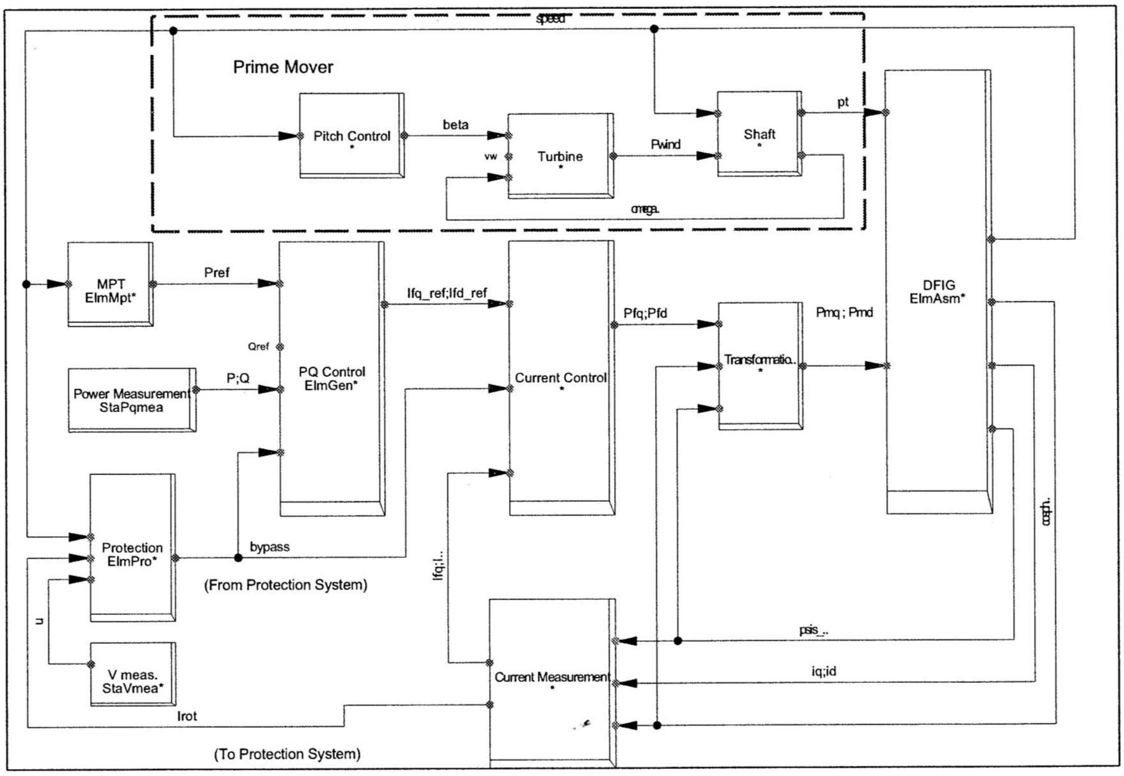
List of reports related to wind turbine component model libraries:

- HElib
  - Hokkanen, Martti. DFIG report, background information from Niiranen and Kauhaniemi .
    - including rotor circuit, converters, crowbar,
    - excluding pitch angle adjustment, power changes, and mechanical losses
    - crowbar acting is satisfactory and generator W-P curve is accurate
    - problems with rotor and stator angles, converter controller very impedance dependent, controller government with hysteresis or some other way…, no saturation effects take into account,
    - 99 pages
  - Hokkanen, Kauhaniemi. Crowbar testing report
    - a generic approach, without details, indicates corresponding between simulations and measurements

        - 20 pages
    - VTT, PM_300kVA_01
        - permanent magnet generator
        - wind source simulated to act as a moment to generator input
        - very short report
    - Kauhaniemi VTT, DTC_plant_01
        - induction machine, direct torque control, frequency converter, L and LC filters, hysteresis control,
        - 10 pages
    - VTT, Wind_1x65_01 and Wind_2x30_01
        - Direct connected induction generator, adjustable constant torque, 1.65 MW and 2.3 MW, compensating capacitors
        - 12 pages
    - VTT, Olos-pilot_V2
        - induction machines, 600 kW/120 kW, compensating capacitors, full MV grid with five loads branches and ability to control transformer tap changer. Secondary PCC, relays, virtual controllable loads, etc.
        - wind turbine – multimass machine (inputs: TL,T_e,W_{pu}), over/under voltage relays, adjustable torque with fixed value,
        - 15 pages
        - Uski-Joutsenvuo, S. Lemström, B. Wind turbine model validated in: Dynamic wind turbine and farm models for power system studies. VTT research report 2007.
    - Haapalainen, erikoistyö, VY, FINkjavo_tuulipuisto, FINkjavoPJK, FINkjavoPJKSL
        - direct connected induction machines 1.65 MW
        - Only part of the report goes through wind components, three wind turbine connections and protection steps (o/u voltage etc.)

- TUT
    - Hailuodon saarekkeen mallinnus, TUT, Hailuoto
        - direct connected induction generator machines,
        - 2x300 kW, 500 kW,
    - Repo, Laaksonen, Järventausta, Mäkinen, Högsåra report 2003
        - Multimass induction machine, 2,3 MW
        - Wind is simulated by control circuit
- Switch
    - User manual

Appendix B: DIgSilent DFIG generator model overview



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