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Advanced Tools for Modeling, Design and Optimization of Wind Turbine Systems

Florin Iov[†], Anca Daniela Hansen[**], Clemens Jauch[**], Poul Sørensen[**] and Frede Blaabjerg[*]

[†*] Institute of Energy Technology, Aalborg University, Denmark
[**] RISØ National Laboratory, Denmark

ABSTRACT

As wind turbine technology and control has advanced over the last decade, this has led to a high penetration of wind turbines into the power system. Whether it be for a large wind turbine or an offshore wind farm with hundreds of MW power capacity, the electrical system has become more and more important in controlling the interaction between the mechanical system of the wind turbine and the main power system. The presence of power electronics in wind turbines improves their controllability with respect not only to its mechanical loads but also to its power quality[1]. This paper presents an overview of a developed simulation platform for the modeling, design and optimization of wind turbines. The ability to simulate the dynamic behavior of wind turbines and the wind turbine grid interaction using four simulation tools (Matlab, Saber, DIgSILENT and HAWC) is investigated, improved and extended.

Keywords: wind turbines, grid interaction, modeling and simulation.

1. Introduction

The motivation for the work presented in this paper is the ever increasing incorporation of wind energy into power networks. In recent years the trend has moved from installations with a few wind turbines to the planning of large wind farms with hundreds of MW capacity. The growing predominance of wind power usage in power networks makes the networks more dependent on and vulnerable to the characteristics of wind energy production. In order for this to be successful, future wind farms must

be able to replace conventional power stations, and thus be active controllable elements in the power supply network. In other words, wind farms must develop power plant characteristics[1]. The two utilities which are responsible for power supply networks in Denmark, Eltra and Elkraft System, have issued requirements[3] that focus on the influence of wind farms on grid stability and power quality, and on the control capabilities of wind farms.

Another consequence of the increased size of wind farms in the future is that the large wind farms will be connected directly to the high voltage transmission grid. Until now, wind turbines and wind farms have been connected to the distribution system, which typically has either 10/20 kV or 50/60 kV grids. Therefore, the main focus has been on the influence of the wind farms on the power quality of the distribution system. For example in

Denmark, this has been regulated by the Danish Utilities Research Institute (DEFU) requirements for grid connection of wind turbines to the distribution system. However, the transmission system operators in Denmark now issue stricter connection requirements for large wind farms if they are connected directly to the transmission system[4]. Moreover, national standards for power quality of wind turbines have recently been supplemented by a new standard for measurement and assessment of power quality of grid-connected wind turbines, namely IEC 61400-21/2001.

Taking into account the above mentioned aspects, the main goal of the presented work was to create model databases in different simulation tools to study system optimization of the wind turbine system[5]. Using this model database a simultaneous optimization of the aerodynamic, mechanical, electrical and control systems can be achieved over the whole range of wind speeds and grid characteristics.

The model databases developed using different simulation tools should be able to support the analysis of the interaction between the mechanical structure of the wind turbine and the electrical grid during different operation modes, like normal or transient operations (cut-in, cut-out and grid faults) as shown in Fig. 1.

Model Database
including parameters

Wind Turbine Design Tools
• Dynamic behavior mechanical
• Grid interaction

Mechanical
structure   **Grid**

Operation   • Start-up and cut-in
Modes   • Shut-down and cut out
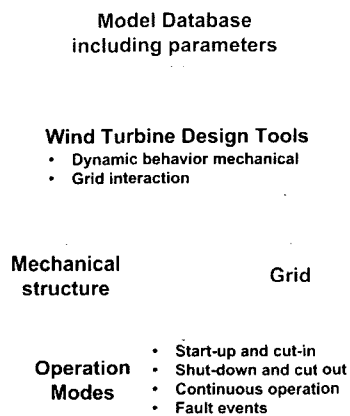   • Continuous operation
         • Fault events

Fig. 1   Structure of the developed Simulation Platform for wind turbine applications

Thus, such models will enable both the potential wind turbine owners and the grid utility technical staff to perform the necessary preliminary studies before investing in wind turbines/farms and connecting them to the grid.

Simulation of the wind turbine interaction with the grid may thus provide valuable information and may even lower the overall grid connection costs.

The main goals of this simulation platform can be summarized as follows:

• To extend the ability of the existing wind turbine design tools to simulate the dynamic behavior of the wind turbines and the wind turbine grid interaction, in continuous, discontinuous and fault situations.

• To extend the existing wind turbine aero-elastic design tools (such as HAWC and FLEX 4/5) with more detailed models of the electrical parts of a wind turbine, to that extent that it makes sense. For example, HAWC can be extended by using reduced order models for the electrical generators and steady state models for power converters, transformers, grid, etc.

• To develop dynamic and steady state models for all components within a wind turbine, which in the long term can be used in a complete optimization of a wind turbine system: models for mechanical parts (wind, drive trains, active and passive stall wind turbines, variable pitch wind turbines), models for generators (squirrel-cage, doubly-fed induction generators, synchronous generators, permanent magnet synchronous generators), models for power converters (soft-starter, back-to-back voltage source converters, multi-level converters, matrix converters), models for three-phase transformers (two-winding, three-winding), models for cables and distribution lines, grid models, etc.

As illustrated in Fig. 2, we will be looking at four different simulation tools for developing new simulation platforms for wind turban applications: HAWC, DIgSILENT, Saber and Matlab/Simulink.
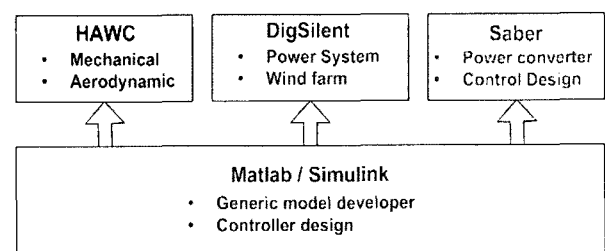
HAWC	DigSilent	Saber
• Mechanical	• Power System	• Power converter
• Aerodynamic	• Wind farm	• Control Design

Matlab / Simulink
• Generic model developer
• Controller design

Fig. 2   Simulation tools used in the developed simulation platform for wind turbine applications

HAWC is an aero-elastic tool developed at RISØ National Laboratory and used in the calculation of dynamic loads on the structure of a wind turbine. It currently focuses on the aerodynamic and mechanical parts of a wind turbine. However, it does not provide sufficient modeling details of the electrical systems necessary for assessing highly controllable wind turbines.

DIgSILENT is a dedicated electrical power system simulation tool used for the assessment of power quality and the analysis of wind turbine interaction with a grid.

Saber is a simulation tool used in circuit and power electronics design which includes electrical, thermal, magnetic and mechanical components. However, this tool is currently not focused on wind turbine applications.

Matlab/Simulink is used as a general model development tool. It is also used for validation of the models[6]. The models are first developed and verified in Matlab/Simulink and then implemented in the other three simulation tools.

Additionally, other simulation tools such as PSCAD/EMTDC might be considered in future.

As illustrated in Fig. 3, the abilities of these simulation tools are complementary and together they can cover all the modeling aspects of the wind turbines, such as mechanical loads, power quality, switching, control and grid faults.

We have decided to develop new models for the main subsystems of a wind turbine because the built-in models

suitable for wind turbine analysis. Moreover, some components, such as wind models and aerodynamic models, are not modeled in these packages. Therefore, we have developed and implemented new models in the considered simulation tools. These models can also be implemented in other simulation tools such as PSCAD/EMTDC.

In order to generalize the model database, the developed models should meet the following requirements:

- models should be open and based on common literature;
- models should have different levels of detail;
- parameters should be easy to determine (physical based most preferable) e.g. datasheets;
- simulation speed should be sufficient;
- models should be user friendly and provide documentation;
- models should be easy to extend with extra modeling features such as saturation, iron losses and deep-bar effect for electrical generators.
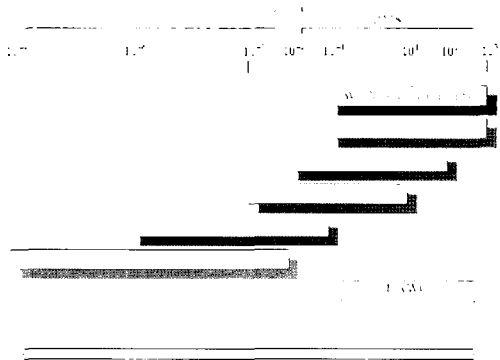

Fig. 3 Modeling aspects and levels in a wind turbine system (Legend: RMS-steady-state, EMT-Electro-Magnetical Transients)

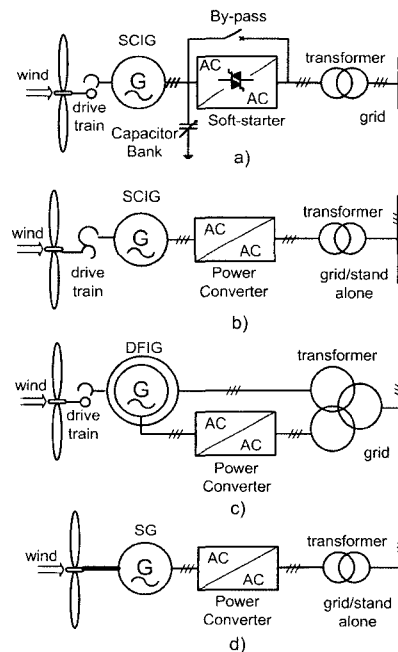from commercial simulation packages are not always

Fig. 4 Basic topologies for wind turbines: a) fixed speed with squirrel-cage induction generator connected directly to the grid, b) variable speed with squirrel-cage induction generator, c) variable speed with doubly-fed induction generator, d) variable speed with direct driven synchronous generator

After the wind turbine component model databases have been developed in the different simulation tools, the next step is to develop models for the most commonly applied wind turbine configurations, as illustrated in Fig. 4.

The "Danish Concept" of directly connecting a wind turbine to the grid shown in Fig. 4a is widely used for power ratings up to 2.3 MW. The scheme consists of a squirrel-cage induction generator (SCIG), connected via a transformer to the grid. This turbine operates at approximately fixed speed (1-2% speed variation) and uses both passive and active stall control concepts. Since a squirrel-cage induction generator always draws reactive power from the grid, a capacitor bank is used in order to compensate for the output power factor. This concept is robust and cheap. However, there are some drawbacks: the wind turbine has to operate at constant speed, it requires a stiff power grid to enable stable operation and it requires a more expensive mechanical construction in order to absorb high mechanical stress[7].

Some manufacturers have developed variable speed wind turbines with a SCIG and a power converter as shown in Fig. 4b. Usually, a back-to-back voltage source converter is used in order to achieve full control of the active and reactive power. Since the power converter is designed to carry a full load this solution is preferred for low power, especially in stand-alone or hybrid systems.

The most attractive topology seems to be the variable speed doubly-fed induction generator (DFIG) as shown in Fig. 4c. Alternatively, there is the semi-variable speed wind turbine, in which the rotor resistance of a wound rotor generator is varied using power electronics. In this way the speed range can be extended up to 10% of the rated value. However, by using a power converter in the rotor circuit, full control of the active and reactive power can be achieved. The main advantage is that the converter power rating is around 25% of the total generator power with a speed range of ± 30%.

Another wind turbine topology that is used is based on a multi-pole synchronous generator, as shown in Fig. 4d. The generator can be an electrically excited (wound rotor) or permanent magnet excited generator. This type of generator is used in gearless applications.

Each of these topologies has benefits and drawbacks. A fixed speed wind turbine is relatively simple, so the price tends to be slightly lower[8]. Since the rotor speed cannot be varied, these turbines must be more robust than the other designs due to the higher structural loads involved.

A variable speed wind turbine generates more energy for a given wind speed time series especially at low wind speed. Moreover, the active and reactive power can be easily controlled and there is less mechanical stress. Unfortunately, the induction generator and power electronics are sensitive to voltage dips caused by faults or switching and so, they are also more expensive. However, costs can be saved on the gearbox.

The major drawback of the direct-driven topologies is the large and relatively heavy generator. Moreover, the power converter has to be designed to handle the full-generated power.

Other wind turbine concepts based on the switched reluctance machine or the transverse flux machine may offer an alternative to the "classic" generators, but they are not considered in our simulations.

First, this paper presents an overview of the simulation tools used in the developed simulation platform. Then, some simulation results for the most common wind turbine topologies are shown.

2. Description of the Selected Simulation Tools

In this section each simulation tool used in the simulation platform is briefly presented with focus on the modeling and simulation time frame aspects[9]-[12]. Some features of the developed models are shown.

2.1 HAWC

HAWC (Horizontal Axis Windturbine Code), developed at RISØ, is a computer aero elastic design program used for predicting load response for a two or three bladed horizontal axis wind turbine over time. HAWC focuses on the frequency scale 0–20 Hz where the main contribution to fatigue loads exist. It is based on a modified Blade Element Momentum(BEM) model for simulation of a dynamic response of a wind turbine[13]. A model of a wind turbine is divided into substructures, which are coupled at nodes as shown in Fig. 5.
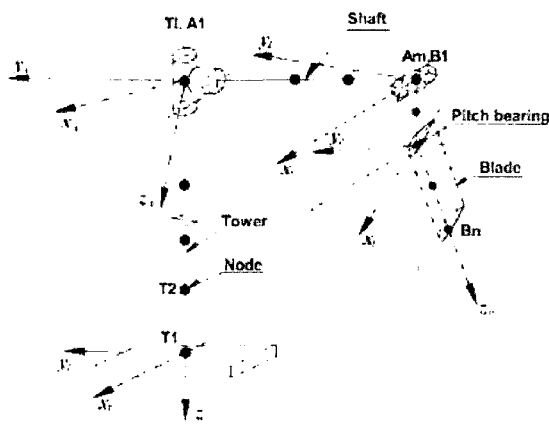
Fig. 5   Substructures and coordinate systems for the structure model in HAWC

This model has been developed over the years and at present it is used extensively by the wind turbine industry.

A complete model for a wind turbine consists of different sub-models such as: a wind model (wind shear, tower shadow, up-flow, yawed flow), a turbulence model (MANN and VEERS models), aerodynamics (blade element momentum model), a structure model (finite element model with 3 substructures: blades, nacelle/shaft and tower), wind turbine controllers (stall, active-stall, pitch, variable-pitch), and wave and current models for offshore wind turbines. These detailed models are used to make detailed calculations of the dynamic loads on the structure of the wind turbine; they are used to study the dynamic behavior of wind turbines in critical situations such as over speed, shutdown, and start up. The model does not, however, provide sufficient details of the electrical system necessary for assessing the behavior of highly controllable wind turbines and analyzing wind turbine grid interaction.

The goal of the HAWC simulation platform was therefore to extend it so that it could better manage some of the electrical aspects of wind turbines. However, as the HAWC code normally operates with a simulation step greater than 20 msec, the extension of HAWC to model electrical components is limited.

Thus, our attention was focused on implementing a dynamic induction generator model as opposed to modifying the existing static one.

Up to this point, the induction generator model used in

HAWC has been a simple static model. This model assumes a linear relationship between the generator speed and torque based on generator slip, which is a simplified implementation of the classic steady-state model. The model is simple, robust and sufficient for making aero elastic calculations. However, such a simplified steady state model does not accurately predict the dynamic performance of an induction machine, and therefore it is insufficient for analyzing wind turbine grid interaction.

The solution is to replace the existing linear static model with a reduced order model of an induction generator which neglects the stator transients. This new model is implemented directly in the HAWC code. This new induction generator model improves the ability of the aero-elastic program to simulate the electrical aspects of the wind turbine. Another strength of this new model is that it can be used to simulate the response of both squirrel-cage induction generators and doubly-fed induction generators.

2.2 DIgSILENT

DIgSILENT is a dedicated electrical power system simulation tool, It is used by the power-system utilities and more and more by the wind turbine industry[14], [15].

DIgSILENT has the ability to build models with different levels of detail. It combines models for electromagnetic transient simulations of instantaneous values with models for electromechanical simulations of RMS values. This makes the models useful for studies of grid fault (transient), power quality and control issues (longer-term). For example, RMS simulations are more appropriate for long simulation periods without transients, as in most studies of power quality and control issues. On the other hand, detailed models of instantaneous EMT values are required for reliable simulations of behavior during grid faults.

DIgSILENT provides both a comprehensive library of models for electrical components of power systems and a dynamic simulation language DSL. There are thus two types of models in DIgSILENT:

- Built-in models – standard electrical component models already existing in the DIgSILENT library, for example: models for generators, motors, controllers, power electronics, dynamic loads and various passive

network elements (e.g. lines, transformers, static loads and shunts). The implementation of these built-in models of the electric components is unfortunately not directly accessible to the user. This limitation makes it difficult to document and, more importantly, to modify the models at the component level;

- DSL models - models created by the user in the dynamic simulation language DSL. For example, the models of wind speed, mechanics, aerodynamics and the control systems of wind turbines are written in this dynamic simulation language. This makes it possible for users to create their own blocks either as modifications of existing models or as completely new models. These new models can be gathered in a library, and their modular structure enables easy modeling of a single wind turbine or even a wind farm. These models are open and accessible and the user can apply them to different wind turbines.

The dynamic wind turbine model simulates the main effects that contribute to the fluctuation of power from a wind turbine. Wind turbine modeling in the power system simulation program DIgSILENT is done at both the component level and the system level.

At the component level the following models have been implemented as DSL models in this simulation platform: the wind model, the aero dynamic model, the mechanical model, control models (that is, capacitor bank control, active stall wind turbine control, active and reactive power control of DFIG, DC-link voltage and unity factor control of DFIG, and variable speed/variable pitch wind turbine control).

At the system level, two wind turbine concepts have been implemented in the power system simulation program DIgSILENT:

- Active stall wind turbine (fixed speed) with induction generator (Fig. 4a);
- Variable speed/variable pitch wind turbine with doubly-fed induction generator DFIG (Fig. 4c).

These wind turbine concept models can be used or even extended for the study of different aspects, such as the assessment of power quality, control strategies, and connection of wind turbines to different types of grid.

These two implemented models are an important step towards the long term objective of developing tools for the study and improvement of the dynamic interaction between wind turbines (or wind farms) and the power systems to which they are connected. These models can easily be extended to model different kinds of wind turbines or wind farms.

2.3 Saber

Saber is a simulation tool used in power circuit and s system design which includes electrical, thermal, magnetic and mechanical components [16]-[17].

Saber is used in the automotive, aerospace, power and IC industries to simulate and analyze systems, sub-systems and components to reduce the need for prototypes. Saber can simulate physical effects in a wind turbine system. It can handle electric, magnetic, thermal and mechanical variables. Different types of analysis can also be performed in Saber. Therefore, it can be used in the analysis of particular aspects of wind turbine systems.

New models can easily be built including most of the physical systems from a wind turbine system, such as electronic, mechanical, optical, or hydraulic systems (or any combination of them).

In order to simulate a wind turbine system several models have been developed and collected into a Saber Toolbox for wind turbine applications. These newly developed models are: a wind model (implements the same algorithm used in DIgSILENT and Matlab/Simulink), an aerodynamic model, a three-mass model for the wind turbine drive train, an *ABC/abc* model for an induction machine (which can be used both for squirrel-cage and wound-rotor induction machines), power converters models (soft-starters, voltage source converters, etc), different modulation strategies for power converters (sinusoidal Pulse Width Modulation with third harmonic insertion, and Space-Vector Modulation), and a grid model (based on the Thevenin equivalent grid).

These newly developed models involve built-in blocks from Saber libraries as well as newly developed blocks written in the MAST language.

The basic components for the two main concepts used in a wind turbine (Fig. 4) are already present in this new Toolbox.

Finally, the developed models can be used or even extended for the study of different aspects of wind turbine

systems such as control for power converters, switching, etc.

2.4 Matlab/Simulink®

MATLAB/Simulink® has become the most used software for the modeling and simulation of dynamic systems [18]. Typical uses include: math and computation, algorithm development, data acquisition, modeling, simulation and prototyping, data analysis, exploration, and visualization; scientific and engineering graphics; application development, including graphical user interface building.

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams. Using S-Functions it is also possible to customize and create user-defined blocks [19]. Models are hierarchical, so the models can be built using both high-level and low-level modeling approaches.

A Matlab/Simulink Toolbox for wind turbine applications has been developed in the simulation platform [6]. This toolbox contains models for the components of a wind turbine system. Basically, all four main wind turbine concepts (Fig. 4) can be simulated using the developed models.

The wind turbine systems contain subsystems with different ranges of the time constants: wind, turbine, generator, power electronics, transformer and grid. Among these components the electrical generators and the power converters need the smallest simulation time step and therefore, these blocks determine the simulation speed. Therefore, all the developed models are implemented for fast simulation speed using Simulink blocks or, alternatively, C S-Functions [20].

The basic components of a wind turbine have been modeled and structured into seven libraries as shown in Fig. 6.

The main libraries from this Toolbox are: Mechanical Components, Electrical Machinery, Power Converters, Common Blocks, Transformations, Measurements, and Control.

The Mechanical Components library contains: wind models, aerodynamic models of the wind turbine rotor, and different types of the drive train model (one-mass model, two-mass model).

The Electrical Machinery Library contains models for electrical machines in dq or ABC/abc reference frame such as a squirrel-cage induction machine, a wound rotor induction machine, a salient-pole synchronous machine and a permanent magnet synchronous machine. Some special models, which include deep-bar effect, reduced order models (neglecting the stator transients) and steady state models have also been developed.
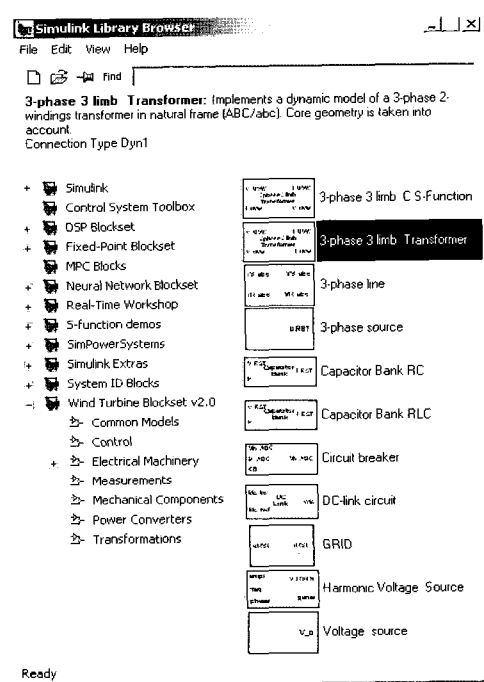

Fig. 6   Wind Turbine Blockset in Matlab/Simulink

The Power Converters library contains models for: 3-phase diode bridge rectifiers, voltage source power converters, soft-starters and different modulation strategies for power converters (sinusoidal PWM, Space-Vector PWM). These models can be used to simulate switching as well as for average simulations. Using the soft-starter model and the ABC/abc model for the induction generator the three main concepts with soft-starter-fed induction generators can be simulated and analyzed.

The Common Models library contains models for 3-phase distribution lines, DC-link circuits, capacitor banks (RC and RLC), three-phase 2-winding transformers and circuit breakers, harmonic voltage sources (EN61000-2-2 standard), and grid models (Thevenin

equivalent). A special model, which takes into account the core geometry as well as iron losses, has been developed for the three-phase two-winding transformer.

The Measurements library contains some special blocks which provide: calculation of the period for a sinusoidal variable, calculation of the grid angle using a phase locked loop, different modes for calculation of active and reactive power, a block to calculate the average wind speed for a given time interval, etc.

The Control library contains blocks such as: an anti wind-up PI-Controller, a maximum power point tracker block based on a look-up table obtained from the wind turbine characteristics, and an active and reactive power control block for a doubly-fed induction generator. This control algorithm for active and reactive power can also be used in connection with a reduced order model of the machine.

Some of the features of this Wind Turbine Toolbox can be summarized as follows:

- All the developed models use basically only Simulink Blocks;
- The toolbox uses the matrix support in order to minimize the number of blocks and connection lines;
- All models which involve a great number of differential equations (such as those for electrical machines, drive-trains and transformers) are also available as 'C' S-Functions for high-speed simulations;
- In order to be able to use different drive-train models the equation of motion is not included in the electrical machine models;

Several research projects have used these models and their accuracy is verified. Their performance has been proven and they can be directly implemented in different simulation tools.

3. Simulation Results

Some simulation results from the considered tools are presented in this section. The wind turbine concepts based on the induction generator (Fig. 4a and Fig. 4c) are implemented and simulated in all four-simulation tools. In the analysis induction generators (squirrel-cage or wound rotor) with a rated power of 2 MW have been used.

3.1 HAWC

Using the new induction generator model implemented in HAWC we discovered a critical coupling between the turbine modes and the generator mode[9]. This coupling was observed several times in the field, without being possible to simulate and explain it. This coupling cannot be simulated unless a very detailed aero-elastic model such as HAWC (where the tower and rotor are not stiff) and a reduced order model of the induction generator (as opposed to a static one) are applied.

Simulations for a 2 MW turbine show for example a coupling between a turbine mode (involving the 3rd flapwise blade mode and the 2nd lateral tower bending mode) and a generator mode at a frequency of 4.5Hz. It turned out that the turbine has a natural frequency close to 4.5Hz, which is the natural frequency of the generator. The turbine mode may therefore couple during operation with the generator mode. The turbine mode close to 4.5Hz is primarily a rotor mode. If the tower is modeled with infinite stiffness, the turbine still has a natural frequency close to 4.5 Hz and the coupling between this rotor mode and generator mode still exists. The critical coupling between the turbine mode and the generator mode is completely removed, if both the blades and tower are assumed to be infinitely stiff (no natural turbine frequency close to 4.5 Hz) or if a linear static generator model is used instead (the old model that was used). This is observed and illustrated in the power spectra of the generator speed and the electrical power in Fig. 7 for a high wind speed of 20 m/s.

The natural frequency of 4.5 Hz is clearly observable in the spectrum where the dynamic model of the generator has been used. However, the peak disappears in the spectrum where only a static generator model is used, leaving a smaller peak at about 4 Hz corresponding to the natural frequency of the turbine mode with which the generator can couple.

The new induction generator model implemented in HAWC thus improves the ability of the aero-elastic program to predict the electrical aspects of the wind turbine. Another strength of the model is that it can be used to simulate the response of both squirrel-cage induction generators and doubly-fed induction generators.
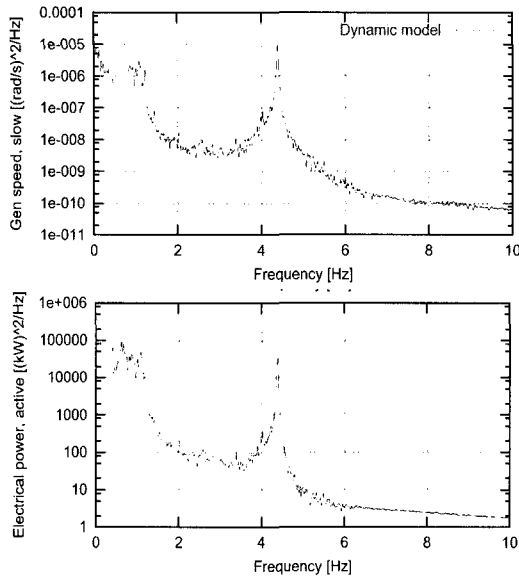
Fig. 7   Coupling between turbine and generator mode at 4.5 Hz, with a static model and with the reduced order model − for low wind speed 6m/s

3.2 DIgSILENT

Two wind turbine concepts implemented in DIgSILENT are presented

a) Active Stall Wind Turbine

The active stall wind turbine has recently become popular. Based on this concept large wind farms such as Nysted (170 MW installed power) have been built. This configuration, basically maintains all the power quality characteristics of a stall-regulated system. In principle, an active stall wind turbine is a stall turbine with a variable pitch angle as shown in Fig. 8.
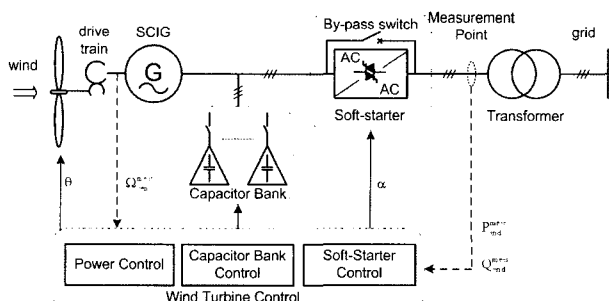
Fig. 8   Block diagram of an active stall controlled wind turbine

The generator of an active stall turbine is a simple squirrel cage induction generator directly connected to the

grid. In order to compensate for the output power factor a capacitor bank is used. A soft-starter is used only during the start-up sequence of the generator in order to limit the in-rush currents and hence reduce the high starting torque.

The main difference between stall and active stall turbines is a pitch system for variable pitch angles, which allows the stall effect to be controlled. An active stall wind turbine has to pitch in a negative direction to limit the power when the electrical power of the wind turbine exceeds nominal power.

The maximum power output of the active stall turbines can be maintained at a constant value. In addition, the aerodynamic efficiency, C_p , can be optimized to a certain extent. The improvements lie thus in greater efficiency of the overall system, due to the use of active stall control. The flexible coupling of the blades to the hub also facilitates emergency stopping and start up. One drawback of the active-stall controlled wind turbine compared to the passive stall one is the higher price. This is due to the pitching mechanism and its controller[21].

The implemented active stall wind turbine controller achieves good power yield with a minimum of pitch actions [22]. Once the overall mean wind speed is at a constant level, pitch angle adjustments are rarely necessary. Allowing the controller to optimize the pitch angle as often as possible, a 10-minute simulation shows that the potential increase in energy would be 1% for wind speeds below nominal wind speed. At speeds beyond the nominal wind speed, the power yield is not improved at all.

Depending on the pitch system, the lost power (due to slow control) may be justified by reduced stress and wear in the pitch system and reduced fatigue loads on the wind turbine. This applies both to power optimization, where the controller strives for maximum power yield by using the moving average of the wind speed signal to find the appropriate pitch angle in a lookup table, and to power limitation where the power output is controlled in a closed control loop.

With a slow control system, substantial overpower in the power limitation mode may cause a problem. This is avoided by an overpower protection feature.

In Fig. 9, the following situation is illustrated: the mean wind speed is 11 m/s until the simulation time is 60 s,

between 60 s and 160 s it is ramped up from 11 m/s to 16 m/s. This corresponds to a slope in mean wind speed of 3 m/s per minute.
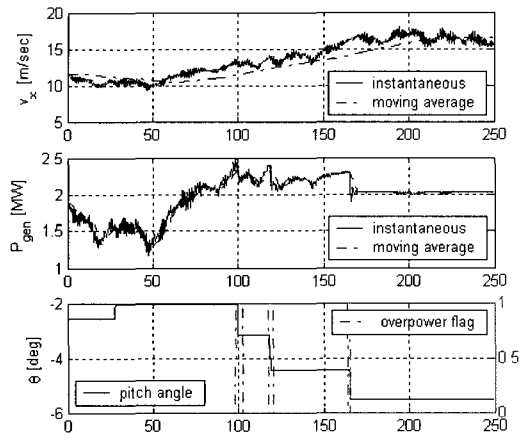

Fig. 9   Simulation results for an active stall controlled wind turbine

The 2 MW turbine starts off in power optimization mode where an increase in pitch angle takes place. As the wind speed increases the turbine enters power limitation mode; a further increase in wind speed causes the average power to exceed 2300 kW (300 kW beyond nominal power, which is the maximum allowed level of tolerable overpower). As soon as overpower is detected the pitch angle is adjusted. Due to the steadily increasing wind speed, it takes three overpower protection operations to permanently reduce the power to a nominal level as can be seen in Fig. 9.

b) Variable Speed/Pitch Wind Turbine with DFIG

The variable speed doubly-fed induction generator wind turbine is the most widely used concept today. The goals of the control system of a variable speed wind turbine with DFIG are:

- To control the power drawn from the wind turbine in order to track the wind turbine optimum operation point;
- To limit the power in the case of high wind speeds;
- To control the reactive power exchanged between the wind turbine generator and the grid.

Fig. 10 shows the overall control system, which has been implemented in DIgSILENT.
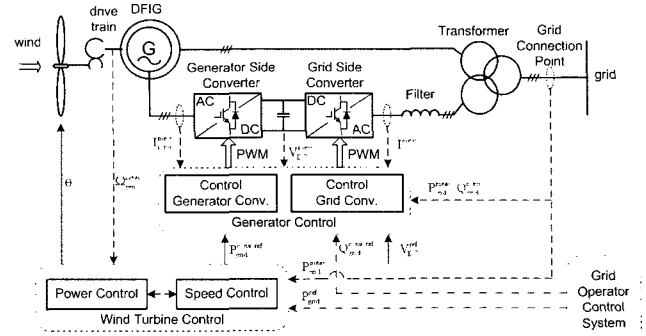

Fig. 10   Block diagram of a variable speed/pitch wind turbine with doubly-fed induction generator

Two hierarchical control levels strongly connected to each other and with different bandwidths, namely DFIG control level and wind turbine control level, have been depicted, designed and implemented [23].

The DFIG control, with a fast dynamic response, contains the electrical control of the power converters and of the doubly-fed induction generator. The wind turbine control, with slow dynamic response, supervises both the pitch system of the wind turbine as well as the active power set point of the DFIG control level.

A vector control approach is adopted for the DFIG control, while two cross-coupled controllers are used to control the wind turbine. These controllers are speed and power limitation controllers, whose goals are to track the wind turbine optimum operation point, to limit the power in the case of high wind speeds and to control the reactive power exchanged between the wind turbine generator and the grid.

The greastest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wide range of wind speeds. Moreover, due to the design of this control method, small changes in generator speed do not lead to large power fluctuations and cause unnecessary transitions between power optimization and power limitation mode. A gain scheduling control of the pitch angle is also implemented in order to compensate for the non-linear aerodynamic characteristics.

Different scenarios are simulated to assess the performance both of the DFIG controller and of the overall control of the variable speed /variable pitch wind turbine. A variable speed wind turbine with a rated power

of 2 MW is used. The rated wind speed is 11.5 m/s and the rated generator speed ω_{gen}^{rated} is 1686 rpm. Fig. 11 shows the simulation results when a turbulent wind speed at a mean value of 22 m/s and a turbulence intensity of 10% is used.

Typical quantities as a function of time (elapsed time 0-600 s) are shown: wind speed, generator speed, the reference of the generator speed, the pitch angle and the generator power on the grid.

This corresponds to the power limitation strategy, where both the speed control loop and power control loop are active. The power control loop is strong and fast, while the speed control loop is much slower, allowing dynamic variations of the generator speed in a predefined range. The power on the grid is limited to 2MW, its variations being less than 2% of the rated power. The reference of the generator is maintained at the nominal speed, while the generator speed varies as the electrical power (that is, the electrical torque is almost constant). The pitch angle reacts to the slow variations in the wind speed..
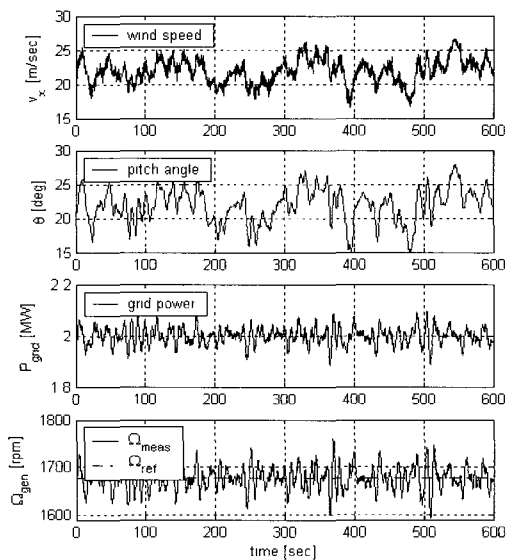

Fig. 11   Simulation results for a variable speed/pitch wind turbine with doubly-fed induction generator with turbulent wind speed

Due to the nonlinear aerodynamic amplification in the system, the gain in the power control loop is a nonlinear function of the pitch angle. A constant gain can cause instability.

3.3 Saber

We investigated the start-up sequence of a 2.2 kW soft-starter-fed squirrel-cage induction machine with a delta connection for the stator windings using the models developed in Saber. The simulation diagram in Saber consists of a voltage source, a soft-starter, a by-pass switch (used in normal operation) and an *ABC/abc* model for induction machine as shown in Fig. 12.
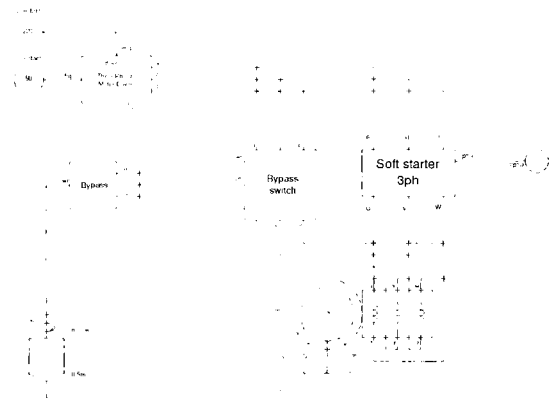

Fig. 12   Saber simulation diagram for a soft-starter-fed induction machine with delta connection for the stator windings

The simulation results in terms of the electromagnetic torque and the shaft speed are shown in Fig. 13.
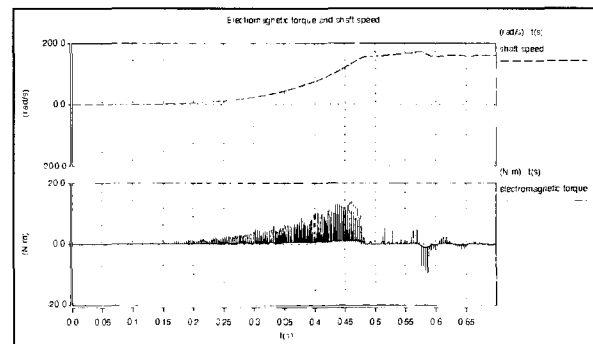

Fig. 13   Start-up sequence for a soft-starter fed induction machine in Saber

A soft-starter fed induction machine can only operate in one of two modes [24], [25], namely Mode 1 when two or three thyristors are conducting and Mode 3 when zero or two thyristors are conducting.

Each of these modes is characterized by some special patterns for the voltages and currents. The voltage and line

current waveforms for these operation modes are shown in Fig. 14 and Fig. 15.
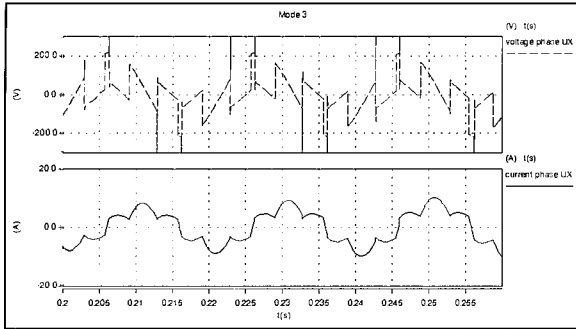

Fig. 14   Typical waveforms for voltage and current in operation Mode 3 for a soft-starter-fed induction machine with delta connection for stator windings
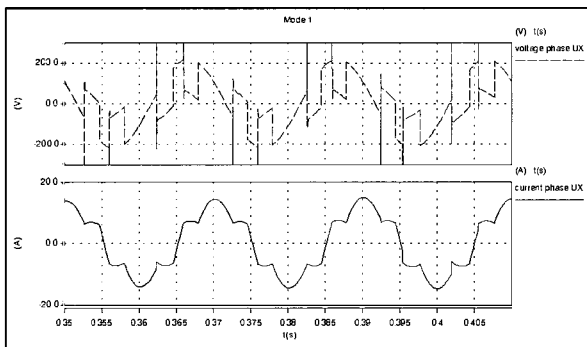

Fig. 15   Typical waveforms for voltage and current in operation Mode 1 for a soft-starter-fed induction machine with delta connection for stator windings

It should be noted that these waveforms are similar to those obtained in Matlab/Simulink (see §3.4a). Since Saber is a dedicated electrical circuit simulation tool, while Matlab/Simulink is based on the mathematical description of the entire model, this simulation validates the mathematical model of the soft-starter used in Matlab/Simulink.

3.4 Matlab/Simulink

a) Start-up sequence of a soft-starter-fed induction generator

We studied the start-up sequence of a soft-starter-fed squirrel-cage induction machine used in wind turbine applications. The induction machine has 2 MW rated power, 690 V / 1700 A rated phase-voltage and rated line

current, respectively (delta connection). The induction machine is connected via a soft-starter to the supply voltage below synchronous speed (1450 rpm). The starting firing angle for the soft-starter is 120°. The equivalent diagram of this system is shown in Fig. 16
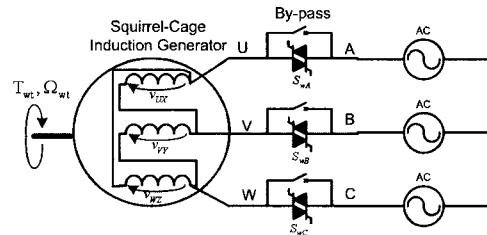

Fig. 16   Equivalent diagram of a fixed-speed wind turbine during start-up sequence.

The Simulink model of this system considers a two-mass model for the wind turbine drive train as shown in Fig. 17.
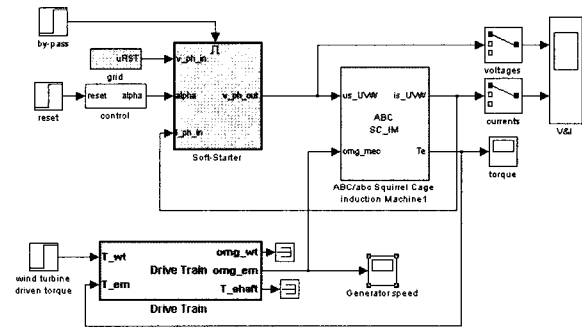

Fig. 17   Simulink diagram of a fixed-speed wind turbine during start-up sequence.

In order to evaluate such a system during the start-up sequence the electromagnetic torque and the rotational speed of the high-speed shaft are analyzed in two cases: direct start-up and using a soft-starter. Fig. 18 shows the simulation results for the direct start-up sequence, while Fig. 19 shows the results when the machine is connected to the grid via a soft-starter.

When the induction machine is connected directly to the grid high starting torque values are recorded as well as a high harmonic content (50 Hz). Large oscillations in the shaft speed are also present. Using a soft-starter the inrush currents and therefore the high-starting torque are limited and the shaft speed is smooth.
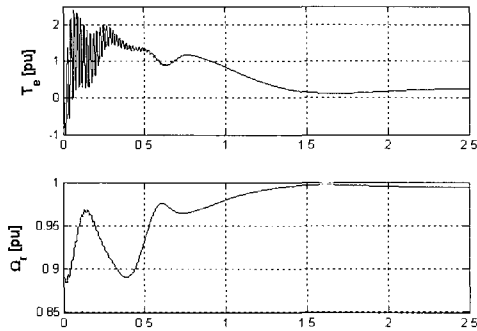
Fig. 18   Electromagnetic torque and shaft speed during the direct start-up sequence of a 2 MW induction machine in wind turbine applications
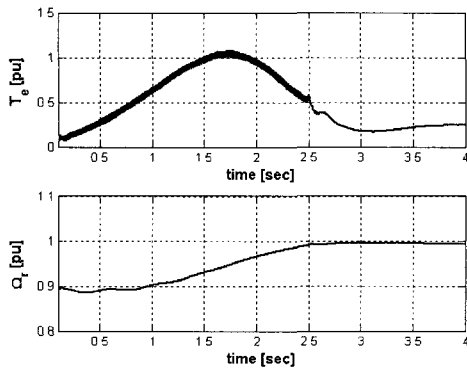

Fig. 19   Electromagnetic torque and shaft speed during start-up sequence of a 2 MW soft-starter-fed induction machine in wind turbine applications

In order to highlight the different operation modes of the soft-starter during the start-up sequence [24] and [25], the phase voltage and the corresponding line current for different firing angles are shown in Fig. 20 and Fig. 21.
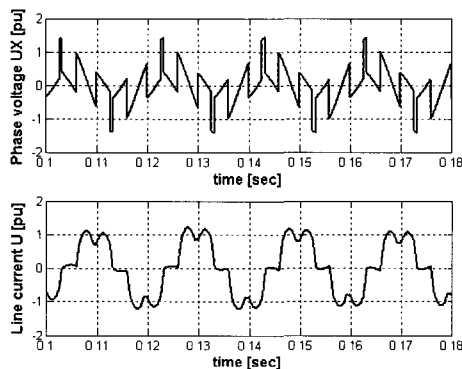

Fig. 20   Phase voltage and line current during the start-up sequence in operation Mode 3
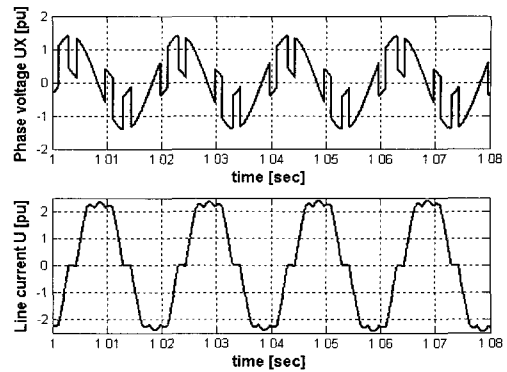

Fig. 21   Phase voltage and line current during the start-up sequence in operation Mode 1

Operation Mode 3 is characterized by a large value for the firing angle of the soft-starter and zero or two thyristors conducting at each moment. Operation Mode 1 corresponds to a small value of the firing angle and two or three thyristors conducting at the same time.

These waveforms can be obtained using only an *ABC/abc* model for the induction machine. Moreover, the *ABC/abc* developed model from the *Wind Turbine Blockset* permits the analysis of both phase and line voltages and currents.

b) Variable Speed/Pitch Wind Turbine with DFIG

Using the available blocks from the "Wind Turbine Blockset" the control of active and reactive power for a 2 MW wind turbine using doubly-fed induction generator (DFIG) has been studied. The Simulink diagram of the system is shown in Fig. 22.

The simulation structure comprises the wind model, drive train model, a DFIG model (written in a synchronous reference frame), the control block for active and reactive power (P&Q) and the optimal control of the entire system.
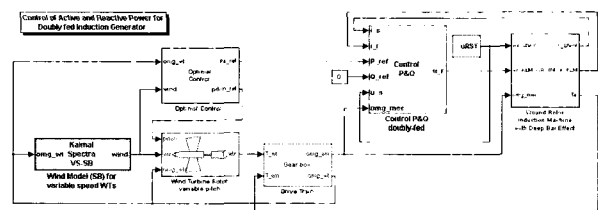

Fig. 22   Simulink diagram of a 2 MW variable speed/pitch wind turbine with DFIG.
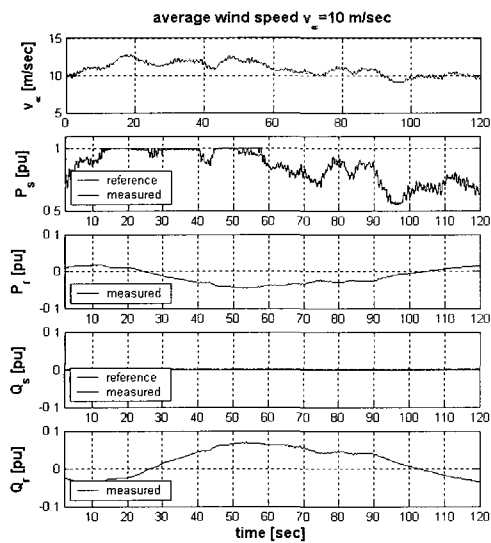
Fig. 23. Simulation results of the active and reactive power control for a DFIG wind turbine.

The optimal control block implements basically the same control strategy as in DIgSILENT. The algorithm used in the P&Q control block can be used with a reduced model for the DFIG [25]. Therefore, the main goal of this simulation is to test the P&Q control algorithm for a future implementation in HAWC. Notice that the power converter has been omitted in this simulation because an average model of the power converter is already included in the P&Q control block.

In order to analyze the control of the active and reactive power for this system a wind time series with an average value of 10 m/sec has been used. The synchronous speed of the machine has been considered as the base value for speed, while the rated power of the machine is the base for the active and reactive power.

The simulation results in terms of the wind time series, active and reactive power, both for the stator and the rotor circuit, are shown in Fig. 23.

It can be observed that the power is limited at the rated value, while the speed is lower than the rated value. The reference of the stator reactive power and the measured one are zero in the entire simulation horizon. Since, the wind speed has been acquired with the inherited sample time from the simulation (0.05 sec) and it is used in the control algorithm, the reference for the stator power is not so smooth and the produced active power follows

identically this reference. In a real system, the wind speed is acquired using a bigger sample time; the average values for the wind speed are calculated in 1minute samples. Due to this filtering of the wind speed, the reference will be much smoother and the output power will not exhibit such fast variations. In our simulation, the averaging block of the wind speed has been omitted in order to study the dynamic performances of the control loops.

The simulation results show a good dynamic response from the control algorithm. Therefore, this algorithm will be implemented in HAWC.

4. Conclusions

An extended simulation platform for modeling, optimizing and designing wind turbines is presented in this paper. Four simulation tools, namely: HAWC, DIgSILENT, Saber and Matlab/Simulink are used in this simulation platform. New models and new control algorithms for wind turbine applications have been developed and tested in these tools. These models can be easily extended to model different kinds of wind turbines or even large wind farms. The performance of these models has been proven and they can be directly implemented in different simulation tools. Dedicated Toolboxes for wind turbine applications in Matlab/Simulink and Saber have been developed.

The developed models and control algorithms will enable both potential wind turbine owners and grid utility technical staff to perform the necessary preliminary studies before investing in and connecting wind turbines/farms to the grid. Simulation of the wind turbine interaction with the grid may thus provide valuable information and may even lower overall grid connection costs.

Acknowledgments

Remarks

Further information about the Simulation Platform can

be found at: www.iet.aau.dk/Research/spp.htm.

Moreover, a beta version of the Matlab/Simulink Toolbox can be downloaded. The published reports related with this project are available upon request.

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Florin Iov received the Dipl. Ing. degree in electrical engineering from Brasov University, Romania in 1993 and the PhD degree from Galati University, Romania in 2003. He was with Galati University, Romania from 1993-2000 as teaching assistant, assistant and then assistant professor. Since 2001 he has been employed at Institute of Energy Technology, Aalborg University, Denmark as research assistant and then research assistant professor. His research areas are in electrical machines, power electronics and drives with special focus on dynamic modelling and control of wind turbines/farms.

Anca D. Hansen was born in Bucharest in Romania, on August 26, 1967. She has received an MSc in mechanic engineering from the Technical University of Bucharest (Romania) in 1991. In 1997 she has received a Ph.D. in modelling and control engineering from Denmark Technical University. She has been employed at Risø National Laboratory in the Wind Energy Department since 1998. She currently holds a position as a senior scientist. Her working field and research projects are on the topics of dynamic modelling and control of wind turbines, as well as dynamic modelling and control of wind farms and on wind farm grid interaction.

Clemens Jauch received the Dipl. Ing. (FH) degree in electrical power engineering from Kiel University of Applied Sciences, Germany, and the Høgskoleingeniør degree in power engineering from the Agder College in Grimstad, Norway. Both degrees he received in 1999. From 1999 to 2001 he was working with the wind turbine manufacturer Nordex Energy in Germany. In 2002 he received the MSc degree in Electrical Power Systems from the University of Bath, Great Britain. Subsequently he worked as research assistant in the Wind Energy department of the research institute Risø National Laboratory in Roskilde, Denmark. There he started doing a Ph.D. on transient stability of wind turbines in the year 2003.

Poul Sørensen was born in Kolding in Denmark, on June 16, 1958. He obtained his M.Sc. from the Technical University of Denmark, Lyngby in 1987. He was employed in the Wind Energy Department of Risø National Laboratory in October 1987, where he is currently working as a senior scientist and project manager. His main field for research is integration of wind power into the power system. He was a member of the IEC working group preparing IEC 61400-21, and is currently a member of the maintenance team MT21. He is also a member of IEA annex XXI on "Dynamic models of wind farms for power system studies".

Frede Blaabjerg received the M.Sc.EE. from Aalborg University, Denmark in 1987, and the PhD. degree from the Institute of Energy Technology, Aalborg University, in 1995. He was employed at ABB-Scandia, Randers, from 1987-1988. During 1988-1992 he was a PhD. student at Aalborg University. He became an Assistant Professor in 1992 at Aalborg University, in 1996 Associate Professor and in 1998 full professor in power electronics and drives the same place. His research areas are in power electronics, static power converters, ac drives, switched reluctance drives, modeling, characterization of power semiconductor devices and simulation, wind turbines and green power inverter. He is the author or co-author of more than 300 publications in his research fields including the book *Control in Power Electronics* (Eds. M.P. Kazmierkowski, R. Krishnan, F. Blaabjerg) 2002, Academic Press. During the last years he has held a number of chairman positions in research policy and research funding bodies in Denmark. He is associated editor of the IEEE Transactions on Industry Applications, IEEE Transactions on Power Electronics, Journal of Power Electronics and of the Danish journal Elteknik. He received the 1995 Angelos Award for his contribution in modulation technique and control of electric drives, and an Annual Teacher prize at Aalborg University, also 1995. In 1998 he received the Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society. He has received four IEEE Prize paper awards during the last six years. He received the C.Y. O'Connor fellowship 2002 from Perth, Australia, the Statoil-prize in 2003 for his contributions in power electronics and the Grundfos-prize in 2004 for his contributions in power electronics and drives.