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

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Abstract - **In the last decade, the high penetration of wind turbines in the power system has been closely related to the advancement of the wind turbine technology and control. The electric system of a large wind turbine as well as of an offshore wind farm with hundreds of MW power capacity has become more and more important in the interaction between the mechanical system of the wind turbine and the main power system. The presence of power electronics in wind turbines improves the controllability of the wind turbines with respect both to its mechanical loads but also to its power quality [1]. This paper makes an overview of a developed simulation platform for modeling, design and optimization of wind turbines. The ability to simulate the dynamic behavior of the wind turbines and the wind turbine grid interaction of four simulation tools (Matlab, Saber, DIgSILENT and HAWC) has been investigated, improved and extended.**

Index Terms— **wind turbines, grid interaction, modeling, simulation.**

I. INTRODUCTION

THE motivation of the work presented in this paper is the ever-increasing wind energy penetration into power networks. In recent years the trend has been moved from installations with a few wind turbines to the planning of large wind farms with more than hundreds of MW of capacity. This increased and concentrated penetration makes the power network more dependent on, and vulnerable to, the wind energy production. This situation means that 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 [2]. 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 future size of wind farms 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 more strict 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 a model database in different simulation tools for a system optimization of the wind turbine system [5]. Using this model database a simultaneous optimization of the aerodynamic, mechanical, electrical and control systems over the whole range of wind speeds and grid characteristics can be achieved.

The developed model database in 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 both during different operation modes, like normal or transient operations (cut-in, cut-out and grid faults) as shown in Fig. 1.

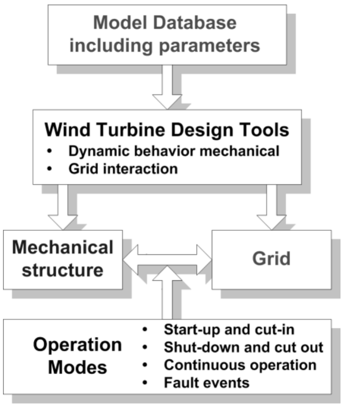


Fig. 1. Structure of the developed Simulation Platform for wind turbine applications.

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 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 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 (e.g. HAWC and FLEX 4/5) with more detailed models for the electrical part of the wind turbine, to that extent that it makes sense. For example, HAWC can be extended with 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 a longer term can be used in a complete optimization of a wind turbine system: models for mechanical part (wind, drive train, active and passive stall wind turbine, variable pitch wind turbine), models for generators (squirrel-cage, doubly-fed induction generator, synchronous generator, permanent magnet synchronous generator), models for power converters (soft-starter, back-to-back voltage source converter, multi-level converter, matrix converter), models for three-phase transformers (two-winding, three-winding), models for cables and distribution lines, grid models, etc.

As illustrated in Fig. 2, the attention in this new developed simulation platform for wind turbine applications is drawn to four different simulation tools: HAWC, DIgSILENT, Saber and Matlab/Simulink.

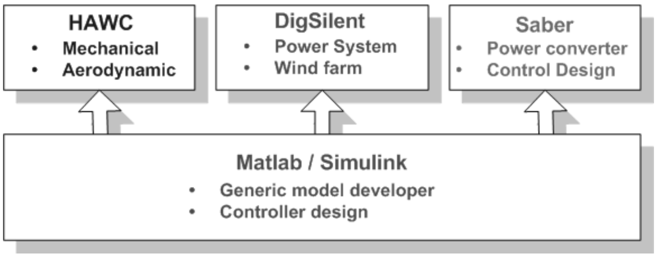


Fig. 2. Simulation tools used in the developed simulation platform for wind turbine applications.

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

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

Saber is a simulation tool used in circuit and power electronics design including 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 developer tool and also 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.

However, other simulation tools e.g. PSCAD/EMTDC might be considered in future.

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

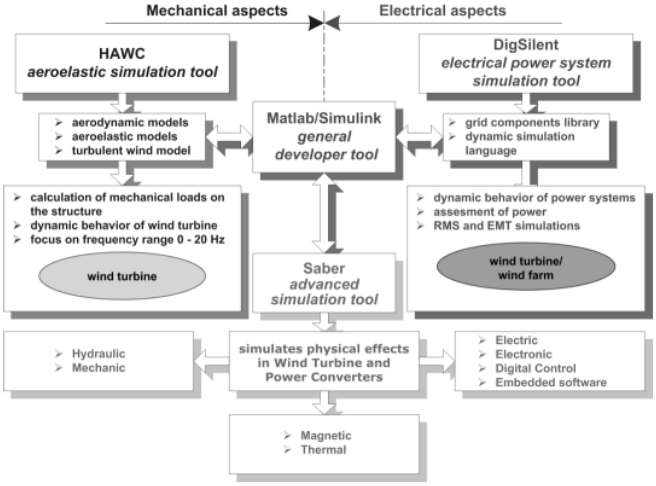


Fig. 3. Complementarities of the selected simulation tools used in the new developed simulation platform for wind turbine applications.

The analysis of these aspects requires a certain simulation tool, a certain model level and a time frame as shown in Fig. 4.

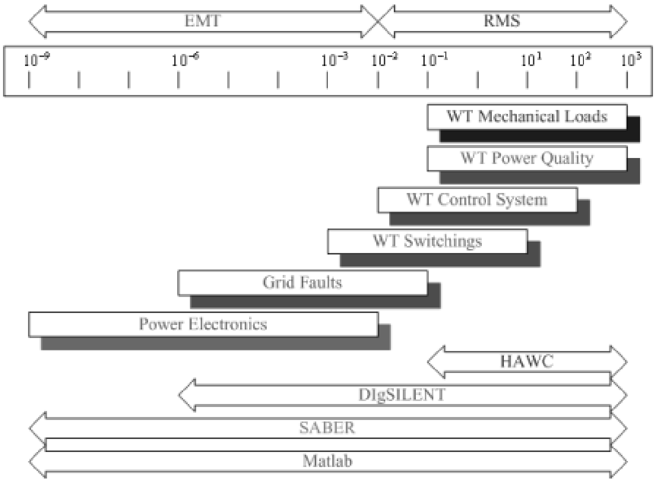


Fig. 4. Modeling aspects and levels in a wind turbine system (Legend: RMS- steady-state, EMT- Electro-Magnetical Transients).

It has been chosen to develop new models for the main subsystems from a wind turbine because the built-in models from the commercial simulation packages are not always suitable for wind turbine analysis. Moreover some components e.g. wind models, aerodynamic models etc., are not modeled in these packages. Therefore, new models have been developed and implemented in the considered simulation tools. These models can also be implemented in other simulation tools e.g. PSCAD/EMTDC.

In order to make the model database general the developed models should meet some requirements as:

- models should be open and based on common literature;
- models with different detailing level;
- parameters easy to determine (physical based most preferable) e.g. datasheets;
- simulation speed important;
- user friendly and available documentation;

- easy to extend with extra modeling features e.g. saturation, iron losses and deep-bar effect for electrical generators.

Based on a developed wind turbine component model database for different simulation tools, the next step is to build up models for the most commonly applied wind turbine configurations, as illustrated in Fig. 5.

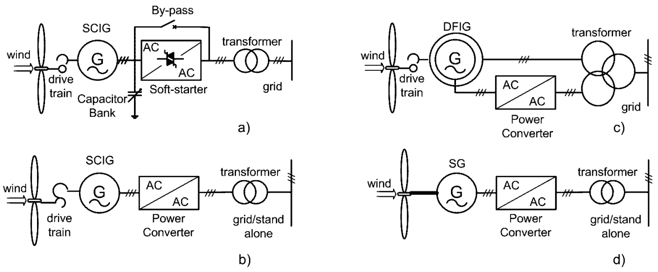


Fig. 5. Basic topologies for wind turbines: a) fixed speed with directly grid connected squirrel-cage induction generator, b) variable speed with squirrel-cage induction generator, c) variable speed with doubly-fed induction generator, d) variable speed with direct driven synchronous generator.

The “Danish Concept” of the directly grid-connected wind turbine shown in Fig. 5a 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 both passive and active stall control concepts are used. Since a squirrel-cage induction generator always draws reactive power from the grid, a capacitor bank is used in order to compensate 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 implies an more expensive mechanical construction in order to be capable 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. 5b. Usually, a back-to-back voltage source converter is used in order to achieve the full control of the active and reactive power. Since the power converter is designed to carry full load this solution is preferred for low power, especially in stand-alone and/or hybrid systems.

The most attractive topology seems to be the variable speed doubly-fed induction generator (DFIG) as shown in Fig. 5c. Alternatively, the semi-variable speed wind turbine concept exists, 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, using a power converter in the rotor circuit a 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 used wind turbine topology is based on a multi-pole synchronous generator, as shown in Fig. 5d. The generator can be electrically excited (wound rotor) or permanent magnet excited type. 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 and/or switching and so, they are also more expensive. However, savings can be done 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 and the transverse flux one can be an alternative to the “classical” generators, but they are not considered yet in the simulation platform.

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.

II. DESCRIPTION OF THE SELECTED SIMULATION TOOLS

In this paragraph 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.

A. HAWC

HAWC (**H**orizontal **A**xis **W**ind turbine **C**ode), developed at RISØ, is a computer aero elastic design program with the purpose of predicting load response for a horizontal axis two or three bladed wind turbines in the time domain. HAWC focus 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 for a wind turbine is divided into substructures, which are coupled at nodes as shown in Fig. 6.

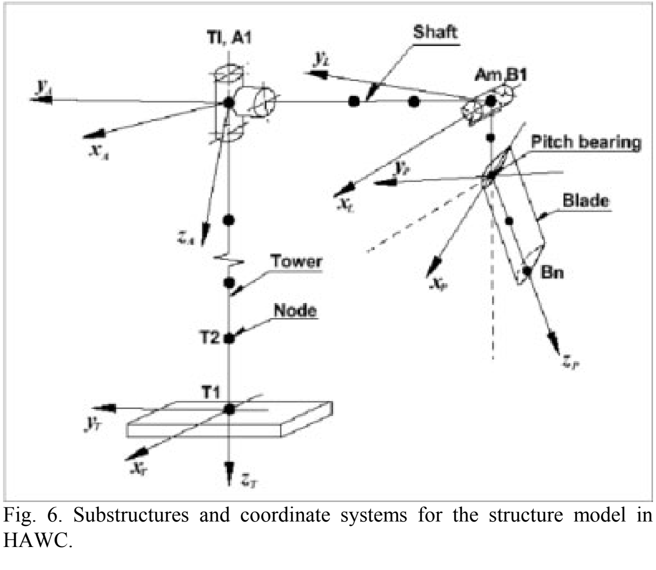


Fig. 6. Substructures and coordinate systems for the structure model in HAWC.

This model has been developed through the years and it is used intensively by the wind turbine industry at the moment.

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

Concerning HAWC, the goal of this simulation platform was therefore to extend it in such a way that it becomes better to cover and manage some electrical aspects. However, as the HAWC code normally operates with a simulation time step bigger than 20 msec, the extension of HAWC with models for some electrical components is possible and makes sense only to some extent.

Thus, the attention was mainly drawn to the implementation of a dynamic induction generator model instead of the existing static one.

The original induction generator model used in HAWC has so far been a rather simple static model, providing a linear relationship between the generator speed and torque based on the generator slip, which is a simplified implementation of the classical steady-state model. The model is simple, robust and sufficient regarding aero elastic calculations. However, such simplified steady state model does not accurately predict the dynamic performance of the induction machine, and therefore it cannot be used properly for analyzing the wind turbine grid interaction.

A reduced order model for induction generator, which neglects the stator transients is therefore implemented directly in the code HAWC and used as a replacement of the existing linear static model. This new induction generator model implemented in HAWC improves thus the ability of the aero-elastic program to predict the electrical aspects of the wind turbine. A strong feature of it is also that it can be used to simulate the response of both squirrel-cage induction generators and doubly-fed induction generators.

B. *DIgSILENT*

DIgSILENT is a dedicated electrical power system simulation tool, used both by the power-system utilities but also more and more by the wind turbine industry [14], [15]. Over the last few years, DIgSILENT has been extended and further developed for wind power applications.

DIgSILENT has the ability to simulate load flow, RMS fluctuations and transient events in the same software environment [14], [15]. It provides models on different levels of detailing. 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 the most studies of power quality and control issues. On the other hand, simulations of instantaneous EMT values with detailed models are required for reliable simulations of the behavior during grid faults.

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

- Built-in models – which are standard electrical component models, already existing in the DIgSILENT library, e.g. 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 even more to modify the models at the component level;
- DSL models - are models created by the user in the dynamic simulation language DSL. For example, the models of the wind speed, the mechanics, aerodynamics and the control systems of the wind turbines are written in such 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 wind turbine as well as of wind farms. They are therefore open/accessible/applied by the user to different wind turbines.

A grid can be modeled in a graphical programming environment, as shown in Fig. 7, where the power system component models (built-in models) are dragged, dropped and connected.

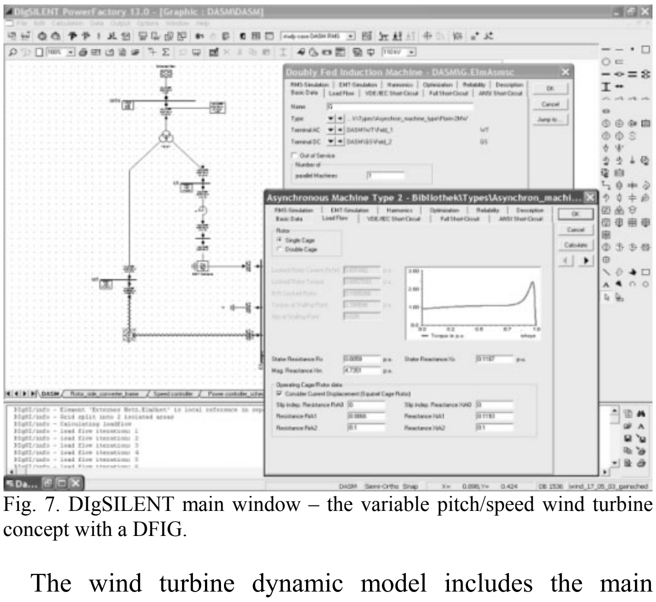


Fig. 7. DIgSILENT main window – the variable pitch/speed wind turbine concept with a DFIG.

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

DIgSILENT provides very detailed models for the electrical components of the wind turbine, and therefore at a component level the following models have been implemented as DSL models in this simulation platform: wind model, aero dynamical model, mechanical model, control models (i.e. capacitor bank control, active stall wind turbine control, active and reactive power control of DFIG, DC-link voltage and unity factor control of DFIG, 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. 5a);
- Variable speed/variable pitch wind turbine with doubly-fed induction generator DFIG (Fig. 5c).

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

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

C. Saber

Saber is a simulation tool used in power circuit and system design including electrical, thermal, magnetic and mechanical components [16]-[20].

Saber is used in the automotive, aerospace, power and IC industry 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 analysis of particular aspects in wind turbine systems.

Saber includes basically two tools namely SaberSketch and SaberScope. SaberSketch contains of a schematic editor and a symbol editor. The user can create a schematic in the schematic editor and then, if the user is using the schematic block as part of a larger system, SaberSketch can be used to generate a symbol for the schematic. SaberScope is a graphical waveform analyzer tool that allows the user to view and analyze simulation results in the form of waveforms displayed on graphs, or as values displayed in lists.

Saber has one of the largest model libraries for the industry. However, new models can easily be built using the existing blocks (graphical modelling), Model Architect Tool and MAST language.

The MAST language lets the user to create a model of any analogue, discrete or control system that can be defined in terms of nonlinear "lumped" algebraic or differential equations. Some extensions are also provided by the use of ideal delay and scheduling. A design can be a combination of more than one functional block to comprise a complete system.

With the MAST language and the Saber simulator, the user can model and simulate most physical systems: electronic, mechanical, optical, hydraulic, etc. (or any combination of them) from a wind turbine system.

In order to simulate a wind turbine system several models have been developed and collected into a Saber Toolbox for wind turbine applications. These new developed models are: wind model (implements the same algorithm which is used also in DIgSILENT and Matlab/Simulink), aerodynamic model, a three-mass model for the wind turbine drive train, an *ABC/abc* model for the induction machine, (it 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), grid model (based on the Thevenin equivalent grid).

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

The basic components for the two main concepts used in wind turbine (Fig. 5) are already present in this new Toolbox. A Saber design for a fixed-speed wind turbine is illustrated in Fig. 8.

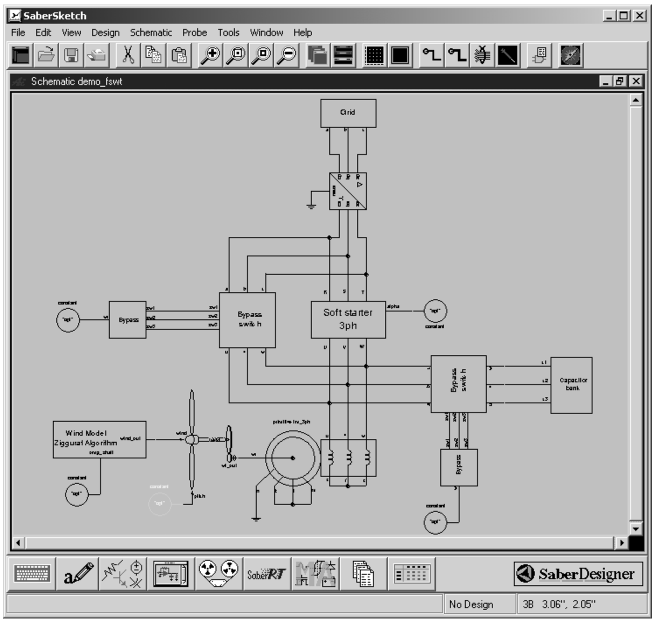


Fig. 8. A model for fixed-speed wind turbine simulated in Saber.

Finally, the developed models can be used or even extended for the study of different aspects in wind turbine systems e.g. control for power converters, switching, etc.

D. Matlab/Simulink

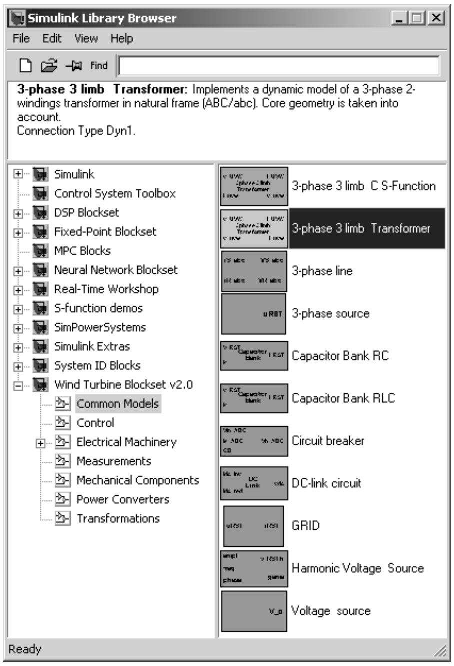
MATLAB/Simulink® has become the most used software for modeling and simulation of dynamic systems [21]. Typical use include: math and computation, algorithm development, data acquisition, modeling, simulation, and prototyping, data analysis, exploration, and visualization; scientific and engineering 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 [22]. 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 from a wind turbine system. Basically, all four main wind turbine concepts (Fig. 5) 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 as C S-Functions [23].

The basic components of a wind turbine have been modeled and structured in to seven libraries as shown in Fig. 9.



3-phase 3 limb Transformer: Implements a dynamic model of a 3-phase 2-windings transformer in natural frame (ABC/abc). Core geometry is taken into account.
Connection Type Dyn1.

Fig. 9. Wind Turbine Blockset in Matlab/Simulink.

The main libraries from this Toolbox are: *Mechanical Components*, *Electrical Machinery*, *Power Converters*, *Common Blocks*, *Transformations*, *Measurements*, *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 e.g. squirrel-cage induction machine, wound rotor induction machine, salient-pole synchronous machine and permanent magnet synchronous machine. Some special models, which include deep-bar effect, reduced order models (neglecting the stator transients) and steady state models have been developed.

The *Power Converters* library contains models for: 3-phase diode bridge rectifier, voltage source power converter, soft-starters and different modulation strategies for power converters (sinusoidal PWM, Space-Vector PWM). These models can be used for simulation of switchings 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 line, DC-link circuit, capacitor bank (RC and RLC), three-phase 2-winding transformer and circuit breaker, harmonic voltage source (EN61000-2-2 standard), grid models (Thevenin equivalent). A special model, which takes into account the core geometry as well as the iron losses, has been developed for the three-phase two-winding transformer.

The *Measurements* library contains some special blocks like: 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 as: anti wind-up PI-Controller, a maximum power point tracker block based on a look-up table obtained from the wind turbine characteristics, 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;
- It uses the matrix support in order to minimize the number of blocks and connection lines;
- All models which involves a great number of differential equations (e.g. electrical machines, drive-trains and transformer) are available also 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;

The developed models have been verified and validated in some research projects with particular analysis. So, the performance of these models is proven and they can be directly implemented in different simulation tools.

III. SIMULATION RESULTS

Some simulation results from the considered tools are presented in this paragraph. The wind turbine concepts based on the induction generator (Fig. 5a and Fig. 5c) are implemented and simulated in all four-simulation tools. In the analysis 2 MW induction generators (squirrel-cage or wound rotor) have been used.

A. HAWC

A very interesting result of the implementation of the new induction generator model in HAWC is a critical coupling between the turbine modes and the generator mode [9]. This coupling was observed several times in real measurements, without being possible to simulate and explain it. This coupling cannot be detected and simulated unless a very detailed aero-elastic model as HAWC (where the tower and rotor are not stiff) and a reduced order model of the induction generator (not 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 4.5 Hz. It turned out that the turbine has a natural frequency close to 4.5 Hz, 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 4.5 Hz is primarily a rotor mode. If the tower is modeled infinitely stiff, 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 a turbine mode and the generator mode is completely removed, if both the blades and tower are assumed infinitely stiff (no natural turbine frequency close to 4.5 Hz) or if a linear static generator model is used instead (the old used model). This is observed and illustrated in the power spectra of the generator speed and the electrical power in Fig. 10 for a high wind speed of 20 m/s.

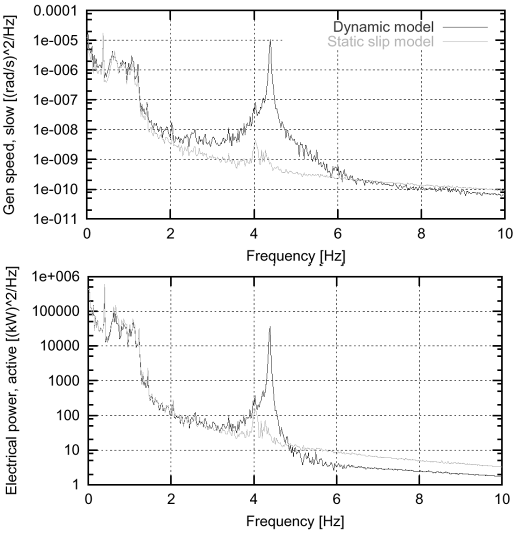


Fig. 10. Coupling between turbine and generator mode at 4.5 Hz, with a static model and with the reduced order model – for low wind speed 6m/s.

The natural frequency of 4.5 Hz is clearly observed 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 improves thus the ability of the aero-elastic program to predict the electrical aspects of the wind turbine. A strong feature of it is also that it can be used to simulate the response of both squirrel-cage induction generators and doubly-fed induction generators.

B. DIgSILENT

1) Active-stall wind turbines

The active stall wind turbine has recently become popular. Based on this concept large wind farms e.g. Nysted (170 MW installed power) have been build. This configuration, basically maintains all the power quality characteristics of the stall-regulated system. An active stall wind turbine is in principle a stall turbine with a variable pitch angle as shown in Fig. 11.

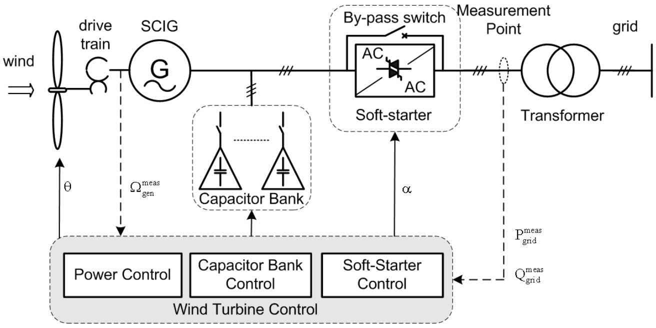


Fig. 11. Block diagram of an active stall controlled wind turbine.

The generator of an active stall turbine is a simple squirrel cage induction generator directly connected to the grid. In order to compensate 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 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 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 controlled to a constant value. In addition the aerodynamic efficiency C_p can be optimized to a certain extend. The improvements lie thus in better utilization 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 comparing with the passive stall one is the higher price due to the pitching mechanism and its controller [24].

Characteristic for the implemented active stall wind turbine controller is that it achieves good power yield with a minimum of pitch actions [25]. Once the overall mean wind speed is at a constant level, pitch angle adjustments are hardly 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. Considering wind speeds beyond 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 in the wind turbine. This applies to power optimization, where the controller strives for maximum power yield by using moving average of the wind speed signal for finding the appropriate pitch angle in a lookup table. This applies also 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 problem. This is avoided by an overpower protection feature.

In Fig. 12, the following situation is illustrated: the mean wind speed is 11 m/s until the simulation time is60 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.

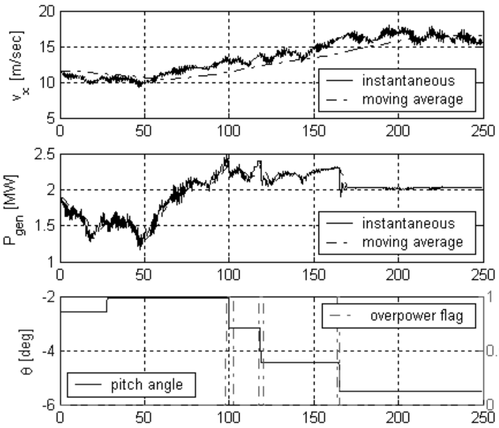


Fig. 12. Simulation results for an active stall controlled wind turbine.

The 2 MW turbine starts off in power optimization mode, where an increase in pitch angle takes place. With increasing wind speed the turbine enters into power limitation mode and a further increase in wind speed lets the average of the power 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 get power permanently down to nominal power as it can be seen in Fig. 12.

2) *Variable speed/pitch wind turbine with DFIG*

The variable speed doubly-fed induction generator wind turbine is today the most widely used concept. The targets 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 interchanged between the wind turbine generator and the grid.

Fig. 13 shows the overall control system, which has been implemented in DIgSILENT. Two hierarchical control levels, strong connected to each other and with different bandwidths namely DFIG control level and wind turbine control level have been depicted, designed and implemented [26].

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 the control of the wind turbine is a result of two cross-coupled controllers. These controllers are a speed and a power limitation controller, which have as goal 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 interchanged between the wind turbine generator and the grid.

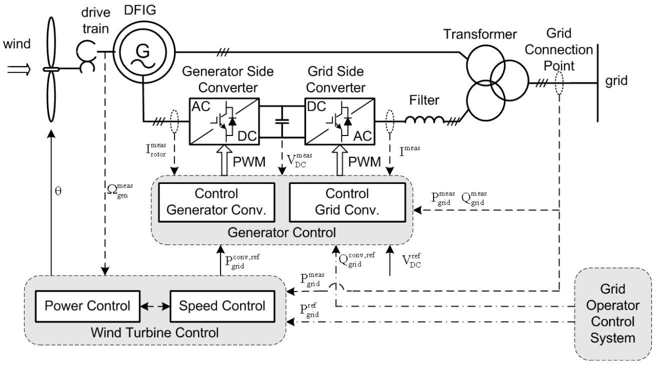


Fig. 13. Block diagram of a variable speed/pitch wind turbine with doubly-fed induction generator.

The strongest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wider range of wind speeds. Moreover, due to the design of this control method, the transition between power optimization mode and power limitation mode is not dominated by large power fluctuations due to small changes in the generator speed. 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 asses the performance both of 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. 14 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.

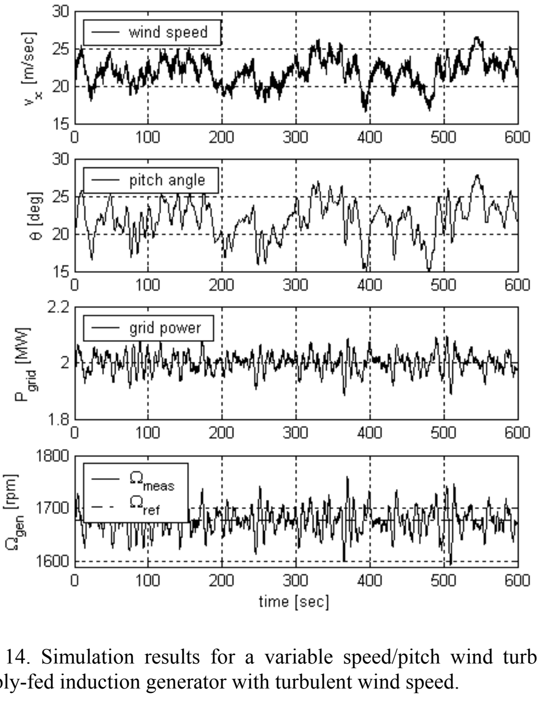


Fig. 14. Simulation results for a variable speed/pitch wind turbine with doubly-fed induction generator with turbulent wind speed.

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. 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 kept constant to the nominal speed, while the generator speed varies as the electrical power (i.e. the electrical torque is almost constant). The pitch angle follows the slow variations in the wind speed.

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

C. Saber

The start-up sequence of a 2.2 kW soft-starter-fed squirrel-cage induction machine with a delta connection for the stator windings has been investigated using the developed models from Saber. The simulation diagram in Saber consists in 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. 15.

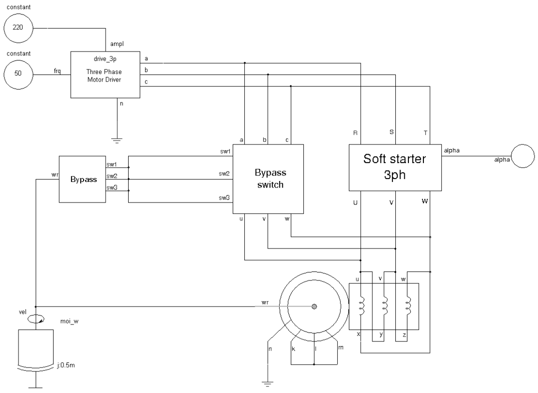


Fig. 15. Saber simulation diagram for a soft-starter-fed induction machine with delta connection for the stator windings.

The simulation results in terms of the electromagnetic torque and the shaft speed are shown in Fig. 16

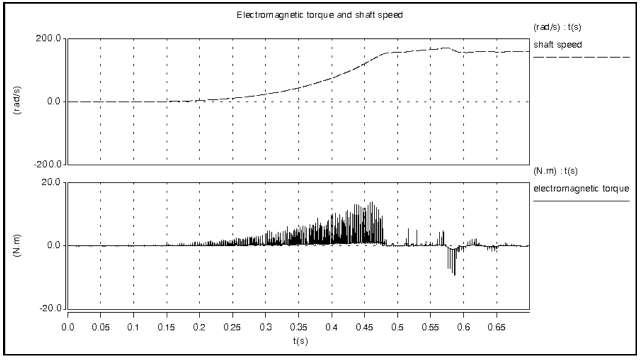


Fig. 16. Start-up sequence for a soft-starter fed induction machine in Saber.

A soft-starter fed induction machine can operate only in two modes of operation [27], [28]:

- Mode 1 - two or three thyristors are conducting;
- Mode 3 - none 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. 17 and Fig. 18.

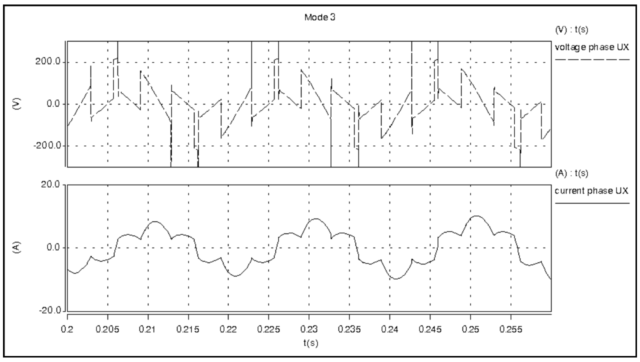


Fig. 17. Typical waveforms for voltage and current in Mode 3 of operation for a soft-starter-fed induction machine with delta connection for stator windings.

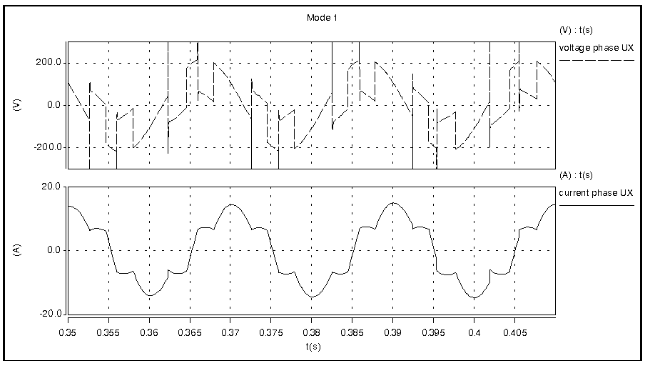


Fig. 18. Typical waveforms for voltage and current in Mode 1 of operation for a soft-starter-fed induction machine with delta connection for stator windings.

It can be noticed that these waveforms are similar with those obtained in Matlab/Simulink (see §D). Since Saber is a dedicated electrical circuit simulation tool, while Matlab/Simulink is based on the mathematical description of the entire model, a good "validation" for the mathematical model of the soft-starter is achieved by this simulation.

D. Matlab/Simulink

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

The start-up sequence of a soft-starter-fed squirrel-cage induction machine, which is used in wind turbine applications, has been studied. 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^o. The equivalent diagram of this system is shown in Fig. 19.

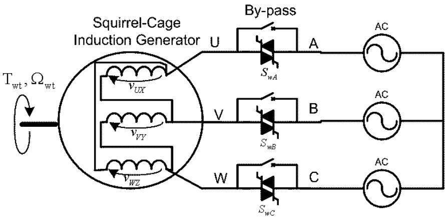


Fig. 19. Equivalent diagram of a fixed-speed wind turbine during start-up sequence.

The Simulink model of this system considers a two-mass model for the wind turbine drive train as shown in Fig. 20.

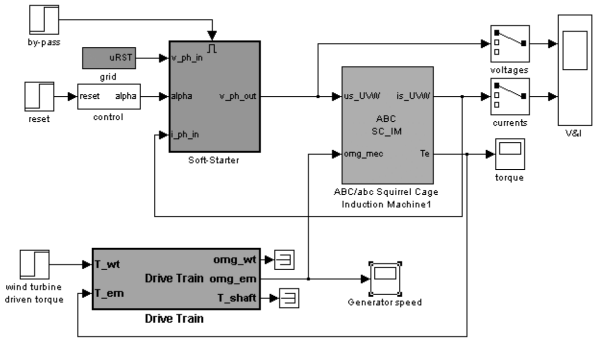


Fig. 20. Simulink diagram of a fixed-speed wind turbine during start-up sequence.

In order to evaluate such a system during the start-up sequence the electromagnetic torque and the rotational speed at the high-speed shaft are analyzed in two cases: direct start-up and using a soft-starter. Fig. 21 shows the simulation results for the direct start-up sequence, while in Fig. 22 is considered that the machine is connected to the grid via a soft-starter.

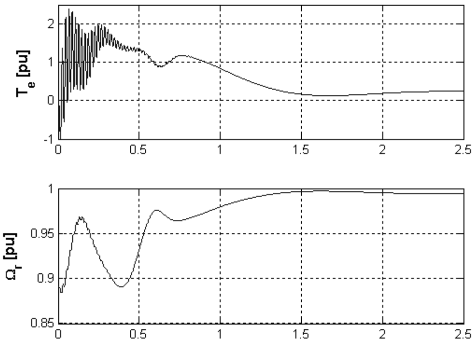


Fig. 21. Electromagnetic torque and shaft speed during the direct start-up sequence for a 2 MW induction machine in wind turbine applications.

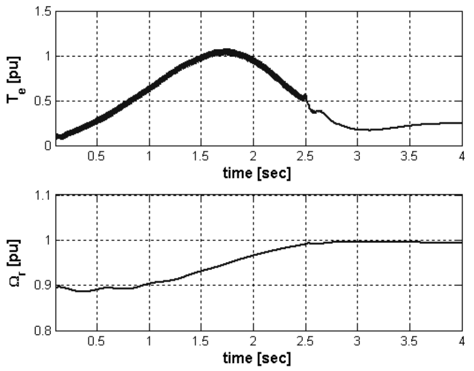


Fig. 22. Electromagnetic torque and shaft speed during start-up sequence for a 2 MW soft-starter-fed induction machine in wind turbine applications.

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.

In order to highlight the different operation modes of the soft-starter during the start-up sequence [27] and [28], the phase voltage and the corresponding line current for different firing angles are shown in Fig. 23 and Fig. 24.

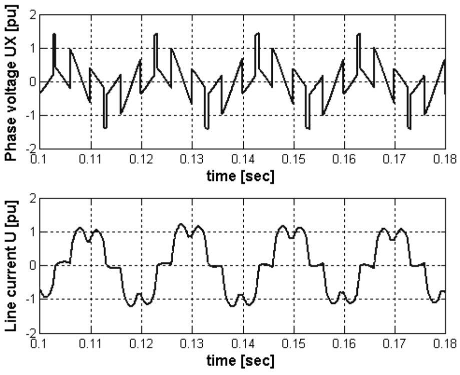


Fig. 23. Phase voltage and line current during the start-up sequence in Mode 3 of operation.

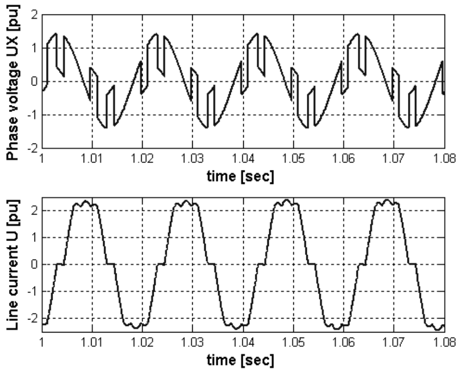


Fig. 24. Phase voltage and line current during the start-up sequence in Mode 1 of operation.

The Mode 3 of operation is characterized by a large value for the firing angle of the soft-starter and none or two thyristors are conducting at each moment. The Mode 1 of operation corresponds to small value of the firing angle and two or three thyristors are 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 to analyze both phase and line voltages and currents.

2) *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. 25.

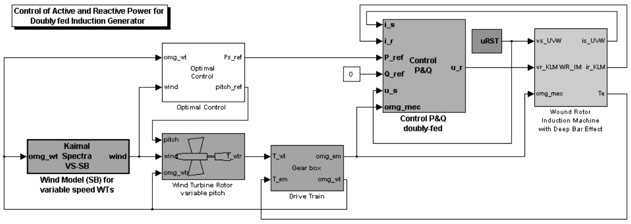


Fig. 25. Simulink diagram of a 2 MW variable speed/pitch wind turbine with DFIG.

The simulation structure comprises the wind model, drive train model, a DFIG model (written in synchronous reference frame), the control block for active and reactive power (P&Q) and the optimal control of the entire system. 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 [29]. 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 it is taken into account 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. 26.

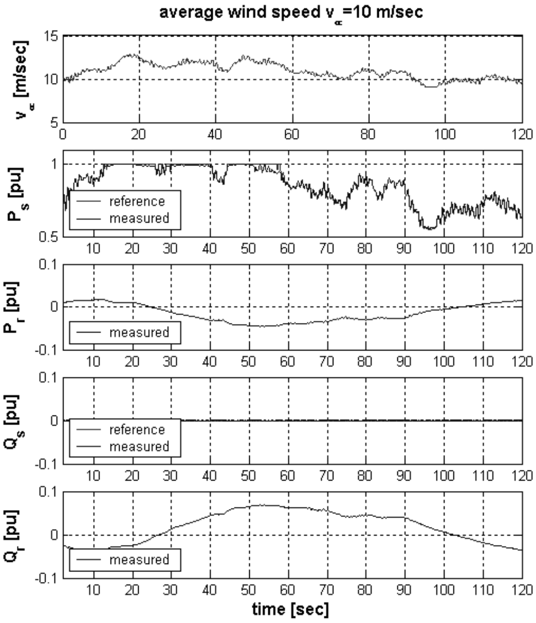


Fig. 26. Simulation results of the active and reactive power control for a DFIG wind turbine.

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 simulation (0.05 sec) and used in the control al+gorithm, the reference for the stator power is not so smooth and the produced active power follows identically this reference. Into a real system the wind speed is acquired with a bigger sample time and some calculations in order to find the average wind speed at each 1 min are performed. Due to this filtering of the wind speed the reference is much more smooth and the output power will not exhibit this fast variations. 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 of the control algorithm and therefore, this algorithm will be implemented in HAWC.

IV. 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 turbines applications have been developed and tested in the considered tools. These models can be easily extended to model different kinds of wind turbines or even large wind farms. The performance of these models is 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 the potential wind turbine owners and the grid utility technical staff to perform the necessary preliminary studies before investing 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 the overall grid connection costs.

ACKNOWLEDGMENT

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