

A SHORT REVIEW OF MODELS FOR GRID-CONNECTED DOUBLY-FED VARIABLE SPEED WIND TURBINES

Martti Hokkanen, Heikki J. Salminen, Timo Vekara

University of Vaasa, P.O. Box 700, FIN-65101 Vaasa, Finland

martti.hokkanen@uwasa.fi, heikki.salminen@uwasa.fi, timo.vekara@uwasa.fi

Abstract— A short review is given on some public simulation models for double-fed, variable speed horizontal axis wind turbines to enable studying the effects of wind power in grid connection. Mostly recent Nordic literature is reviewed.

The paper assesses the background for atmospheric, fluid dynamic and stochastic models, as well as technology-related aerodynamic models for wind turbines, which are needed in order to produce realistic input to the electromechanical system. The stochastic nature of wind represents special challenges in connection of wind power to the grid. Models contain features from engineering and physics.

Index Terms— Doubly-fed induction generator, grid-connected, modeling, simulation, variable-speed, wind turbines

1 INTRODUCTION

WIND turbines, when connected to a weak grid, or a large amount of wind power connected to a more robust grid, may give rise to stability problems, which can be studied by modeling and simulation. The stochastic and unpredictable nature of wind as an energy source creates special problems for control and modeling. For realistic results, the time variation of power output due to wind speed variations needs to be assessed. This variation, giving rise to fluctuations in voltage, frequency and phase angle, could lead to interference and problems with the grid. As a result of the scientific research in meteorology, fluid dynamics, aerodynamic theory, and other physical and engineering sciences, we now have at our disposal improved accurate methods, which narrow down the amount of uncertainties.

Most of the new wind turbines at present are horizontal axis machines. Variable speed wind turbines have become a dominating class of wind turbines, due to their benefits associated with increased turbine size, as described in [1]. Hansen *et al.* in [2] thoroughly present the most common configurations of wind turbines. The wind turbines belong to one of the following three main categories:

- i* fixed speed with directly grid-coupled (asynchronous) squirrel cage induction generator,
- ii* variable speed with doubly-fed induction generator, or
- iii* variable speed based on a direct drive synchronous generator.

This paper, although limited in size, attempts to shed some light on the state of the modeling art as presented mostly in the Nordic literature. We focus on the variable speed, doubly-fed generator concept with a frequency converter that directly controls the currents in the rotor windings. In the MW range, variable speed wind turbines have become one of the most attractive types due to their features given by electronic power converters.

The doubly-fed induction generator can supply power at constant voltage and constant frequency while the rotor speed varies. Constant frequency control is one of the main techniques used in variable speed wind energy conversion system as in [3], [4], [2], [5], [6], [7], [8], [9], [10], [11], [12], [13], Bose [14] pp 308-319, [15], [16], and Leonhard [17] pp. 287-306. Doubly-fed induction generator (DFIG), shown in Fig. 1, is very attractive because the rotor power handled by the converter is a fraction of the total wind turbine power. Because of the converter size, losses and costs are much smaller than in a full size converter as in [18], [19]. Fig. 1 illustrates the doubly-fed induction generator concept, which allows operation at a limited range of speed and power.

Moreover, harmonics are small and distortion relatively low. However, the gearbox is still needed, and a the doubly-fed machine can be a) wound rotor with slip rings, b) doubly-fed brushless machine BDFM described in [20], or c) doubly-fed brushless reluctance machine, as in [1].

The DFIG concept consists of a wound rotor induction generator (WRIG) with stator windings directly connected to the grid and the rotor windings connected to the partial scale (less than 30% generator rating) back-to-back converter, which is a four-quadrant converter. Thus, the converter size depends on a) total generator power and b) selected speed range.

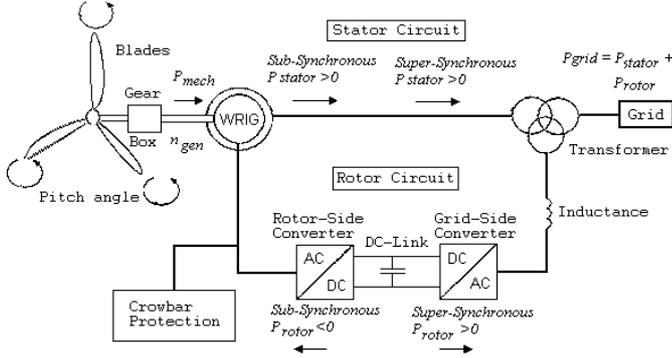


Fig. 1. Principle diagram of the power flow in doubly-fed induction generator.

The DFIG can produce or absorb an amount of reactive power to or from the grid, and that is important when DFIG is connected to a weak grid and voltage control can be regarded as an advantage, as explained in [19], [9].

The viewpoint of this paper is on the modeling of the electromechanics and control system of the doubly-fed asynchronous grid-connected wind turbine. We emphasize that this review is not comprehensive, but it is intended to serve as a start for future studies.

2 MODELING AND SIMULATION OF DOUBLY-FED WIND TURBINE

A. Operating principle

The DFIG concept consists of a wound rotor induction generator with stator windings directly connected to the grid, and the rotor windings connected to the back-to-back converter. The two converters are usually conventional pulse width modulated, voltage-source converters, as in Fig. 1. Some arrangements do not include a transformer, and the generator winding ratio between stator and rotor can be set to other values than 1:1. However, the converter provides reactive power to the DFIG. The generator is working in sub or super synchronous state, i.e. slip is positive ($s > 0$) or negative ($s < 0$), respectively. If the stator and rotor losses are neglected, the power through the converters, the slip power, can be expressed as slip, s multiplied by stator power P_{stator}

$$P_{rotor} = s P_{stator} \quad (1)$$

P_{stator} can also be expressed by using the grid power P_{grid}

$$P_{stator} = 1 / (1-s) P_{gr} = \eta_g P_m / (1-s) \quad (2)$$

where η_g is the generator efficiency and P_m is the mechanical power. Depending on whether the slip is positive or negative, power is fed into or out of the rotor through the converters. In both cases, the stator is feeding power or energy to the grid, i.e., $P_{stator} > 0$ as in [4].

Referring to modeling of grid-connected doubly-fed tur-

bines, perhaps the most relevant recent academic theses are made by Petrú [15], on the wind turbine-grid interaction, by Akhmatov [9], who addresses to the broader view of electric power systems with large amount of wind power; whereas Ottersten in [10] focuses on control of back-to-back converters and sensorless induction machine drives, and Rosas focuses on the dynamic influences of wind power to the grid [6].

Of the rich literature, we would like to pick up some. Recently Marques, Pinheiro, Gründling, Pinheiro, and Hey [20] have published a review paper on the main types of variable speed wind turbines. One of the first papers on doubly-fed concept was written by Pena, Clare, and Asher, who in [3] present an optimum control strategy and its practical implementation on an experimental DFIG set-up. Additionally, in his licentiate thesis Petersson dealt with the analysis, modeling, and control of the doubly-fed induction machine used as a wind turbine generator [7].

In recent research, a fair amount of work deals with modeling of the doubly-fed wind turbine. A fundamental study on modeling of wind turbines for power system studies is the PhD thesis of Petrú, [15]. Norheim, Uhlen, Tande, Toftevaag, and Pálsson [21] suggested a proper model for a doubly-fed induction generator with its controllers. A rough block diagram of a wind turbine with the main variables and controller is shown in Fig. 2.

Special topics, which may be included in models, include:

- i Saturation, which appears when dynamic generator braking happens, or in case of sudden change in speed, in case of faults or outages, or removal from the grid in presence of 3-phase unbalance, explained in [22] and [23].
- ii Torque pulsation compensation control needs to be done so the wind generator remains in connection to the grid in case of unbalance, as in [8].
- iii Modeling of three level converters, as described in [24].
- iv Three level converters produce much lower distortion than two level converters, so the usage of these will increase in large wind power applications.
- v Current source converters, a new type of semiconductor, as in Salo [25].
- vi Modeling of matrix converter.

B. About modeling and simulation

Simulations produce better and more detailed results due to

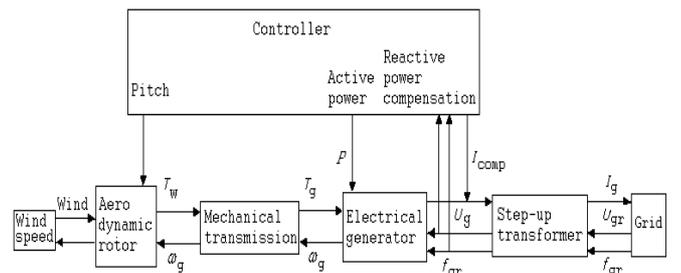


Fig. 2. Block diagram of a wind turbine with control variables.

more accurate and reliable simulation programs. Development in this area is fast following innovations in computer technology.

C. About simulation programs

Currently, a variety of simulation programs exists for use in the special purposes in wind power engineering.

Some simulation programs, which can be used for studying effects of power generation by wind turbines to the grid:

- i* BLADED for Windows[®], overall wind turbine modeling
- ii* DIgSILENT[®]
- iii* MATLAB[®] and Simulink[®]
- iv* PSCAD[®]
- v* PSS/E[®]
- vi* SIMPOW[®]

Hansen, Jauch, Sørensen, Iov, and Blaabjerg [5] describe the dynamic wind turbine models implemented in DIgSILENT. They provide a description of modeling, on a component level, as well as on a system level.

In [26], Sørensen, Hansen, Janosi, Bech, and Bak-Jensen demonstrate the implementation of a dynamic model for a wind farm in DIgSILENT. A way to improve simulations at higher wind speeds, by extending the wind model, was suggested. The results were verified by empirical data.

Some desired modeling features in grid connection to achieve high power quality are presented in [27]:

- i* Avoidance of inrush current during start.
- ii* Infinitely variable power factor control.
- iii* Grid voltage control.
- iv* Power gradient control.
- v* Rated power/torque control.
- vi* Fast fault detection and immediate power electronic trip.
- vii* Extremely low total harmonic distortion level to reduce converter size and sine filters.

An example of a selection of software and their use is presented in [28] including SWIFT, a stochastic wind field simulation program for wind field modeling, PHATAS, to simulate and analyze wind turbines, and WAKEFARM, for making wind farm design calculations.

2.1 WIND

We shall present some literature dealing with things to be considered when trying to tackle the complex problem of how to model wind.

Petersen, Mortensen, Lundberg, Højstrup, and Frank [29] describe, among other things, the basic concepts of boundary layer meteorology, wind shear, atmospheric turbulence and wind climatology.

Wind direction information and local geographic effects need to be included in models for an accurate description of the actual wind environment at the site. A study by Gross, Frey, and Trute indicates that, calculating the local effects by numerical methods predicted, in conjunction with the WASP model, the yearly production to within 2% [30].

Crespo, Hernández, and Fransden made a survey on the state-of-the art of modeling the effects of other turbines on the wind (wakes) [31]. The special topic of northern climate conditions, the effects of inversions and terrain roughness variations (mainly due to snow) on wind turbines located fell tops were discussed by Petersen, Hyvönen, and Tammelin [32]. Dabin, Leclerc, Masson, and Alinot deal with similar issues [33], obviously with emphasis on the conditions in northern parts of Canada. Alinot and Masson continue on the subject of thermal stratification, [34], [35].

The effect of roughness of sea surface on wind, and how to model it, is assessed by Frank, Larsen, and Højstrup [36].

Probability distribution models

Wind models may roughly be divided into two categories, the probability distribution models and the time series models.

The wind variation, for feasibility studies and turbine design optimization, is described by the Weibull distribution. This probability distribution includes all of the wind directions and all time scales present.

In some areas, such as the ones that experience the movements of the monsoon system, the wind speed probability distribution, due to two dominant wind speed sectors, is clearly bi-modal. An emergent distribution will give better results in such cases [37]. A comparison of some of the probability distribution models is shown in Table I.

TABLE I
PROBABILITY DISTRIBUTION MODELS

Distribution type	Applicability	Properties
<i>Rayleigh</i>	Rough general estimates	Fixed shape parameter
<i>Weibull</i>	Site-specific estimates	Shape parameter adjustable to local conditions
<i>Emergent</i>	Site-specific estimates	The weighted sum of the Weibull distributions from all the directional sectors.

The probability distribution models do not contain any information about the nature of the variations.

Time series models

The wind has periodic properties that represent distinct features on a large time scale. The different time scales may be classified according to Table II.

In the wind speed spectrum, periodic variations in a larger time scale than the expected lifetime of a wind power plant can be found, down to time scales of milliseconds. Larger time-scales are interesting with respect to plant pay-back time, structural loading considerations, and production scheduling. On the other hand, much shorter timescales of gustiness and turbulence may affect power quality.

Descriptions of mean gust shapes for extreme load calculations are dealt with by Larsen, Bierbooms and Hansen in [38]. Deterministic discrete gust models from the various standards are explained in the context of extreme loads, in [39]. Kelley and Osgood [40] treated the modeling of turbulence/rotor interactions by wavelet analysis.

The effects of turbulence were studied in practice by Engström, Ganander, and Lindström [41], [42]. Based on the observations, they point out that the periodic short-term power variations in the output of wind turbines are totally dominated by turbulence.

Lungu and van Gelder [43], [44] treated the subject of wind turbulence characteristics, with applications to wind codes.

TABLE II
TIME SERIES MODELS

Time scale	Phenomenon	Timespan	Effect
Long term	Periodical	Years	Pay-back time calculations
Long term	Seasonal variation	5-10 months	Production forecasts
Intermediate	Synoptic Passage of weather systems	Days	Production forecasts
Intermediate	Diurnal variation	Hours	Production forecasts
Short term	Gusts Turbulence	Minutes (seconds)	Stability Power quality

Another type of classification would be descriptive, vs. predictive models. Models used for simulations would predominantly fall in the former category, whereas models of the latter category are found in weather forecasting, and can be used for wind power production forecasts.

2.2 WIND TURBINE AERODYNAMICS

Table III gives some indication of the applicability of the different types of aerodynamic models used for wind turbine aerodynamics modeling, along with references to the literature.

TABLE III
WIND TURBINE AERODYNAMIC MODELS

Model	Applicability	References
<i>Actuator disc</i>	Rough general estimates	[39], [45], [46]
<i>Rotor disc</i>	Performance calculations	[39] pp. 46-51
<i>Vortex cylinder model</i>	Performance calculations	[39] pp. 51-53
<i>Differential actuator disc</i>	Performance calculations of greater accuracy	[47], [48]
<i>Blade element theory</i>	Forces acting on a single blade	[39] pp.60-61
<i>Blade element model</i>	Performance calculations of greater accuracy	[39] pp. 61-64
<i>model-momentum theory (BEM)</i>		
<i>Navier-Stokes 2D</i>	Development of blade profiles	[49]
<i>Navier-Stokes 3D</i>	Performance calculations and flow detail	[50], [51], [52], [53]

Different levels in complexity of modeling exist. Models range from an actuator disc theory based correlation, via the blade element theory, to a Navier-Stokes 3D treatment. A nice review of state of art aerodynamics for wind turbines has been given by Snel [54].

The actuator disc theory is the classical approach for wind turbine aerodynamics modeling. The rotor disc theory adds a description of circulation, induced by the rotor blades. It is not based on description of actual blade geometry. The vortex disc

model includes an axial vortex to the model, such as observed in connection of the operation of a real turbine. The differential actuator disc theory is the most advanced variant of actuator disc model based theories. It incorporates the possibility of introducing the aerodynamic action of real blades to the model.

Regularly, the actuator disk theory is applied, which is described in the literature, e.g. Burton, Sharpe, Jenkins, and Bossanyi [39] pp. 42-46; Heier [55] pp. 22-24.

The actuator disc based models have been further refined by inclusions that correct the effects of yaw and rotor coning. Glauert (1926) presented the yawed rotor momentum theory [39] pp. 99 – 103. Mikkelsen, Sorensen, and Shen [56] study coning effects by BEM and Navier-Stokes methods.

A recent contribution by van Kuik [46] addresses to the fact that the actuator disc theory assumes some non-physical details (incontinuities in the velocity and pressure field gradients).

The most advanced type of modeling, the full 3D or Navier-Stokes based modeling, in principle can reproduce the whole flow field in detail. However, problems with numerical modeling, the correct representation of turbulence phenomena, near-wall phenomena, etc., make this a very challenging modeling approach. In practice, it seems that the overall performance of the turbine is predicted with greater accuracy by the simpler methods. The 3D treatment, however, is indispensable for detailed studies of flow behavior on the blades.

Turbulence, unsteadiness of the flow, and the local speed variations of the mean flow velocity will affect the rotor aerodynamics by altering local blade attack angles and flow patterns, thus altering the output torque.

Leishman [57] reflects on the state-of-the-art, and the challenges in modeling of the unsteady aerodynamics of wind turbines. He points out the modeling of the rotor wake and the modeling of the unsteady aerodynamics of the rotor blade sections as the two key topics that need consideration in wind energy modeling.

For modeling of unsteady operation, the coupling to the mechanical and to the electromechanical system must be made. Damping, by air surrounding the rotor, among other things, as well as the inertia of the rotor and of the other components in the shaft assembly have to be included. In addition to this, the flexibility of the interconnecting shafts, possible slack, etc. need to be considered. In addition, the coupling to the generator itself must be made.

A. The power coefficient

Based on the actuator disk theory, the instantaneous turbine power output P_t can be expressed as

$$P_t = \frac{1}{2} \rho C_p A U_\infty^3. \quad (3)$$

Here ρ = air density
 C_p = the power coefficient
 A = rotor swept area, and
 U_∞ = flow velocity, far from the rotor

With this approach, the complications of the real world can

be thought of as having been immersed in the power coefficient C_p , and in the random nature of wind speed U_∞ .

According to the theory, there is an optimal axial flow induction factor a , which is not dependent on wind speed. The optimal value $a = 1/3$ corresponds to the maximum value of $16/27$ for C_p , known as the Betz limit.

The actuator disc theory can be expanded to the rotor disc theory [39], pp. 46-51. This theory takes into account the action of rotor blades. The above-mentioned results from the actuator disc theory hold. The rotor disc theory introduces another important variable, the tip speed ratio $\lambda = \Omega R/U_\infty$, where Ω is the angular speed of the rotor. R is the rotor radius, and U_∞ is the (upstream) flow velocity, far from the rotor. This type of model yields a dependency of the power coefficient on the tip speed, and on the rotor geometry. More elaborate models, such as the blade element - momentum theory (BEM), give similar results, such that the characteristic values of a rotor can be represented in the above mentioned dimensionless variables, $C_p = f(\lambda)$.

With fully variable speed configuration, a wind turbine would be able to operate at the optimum axial flow induction factor at all times, save for dynamic effects, and for the need of power limitation.

Another dimensionless variable is needed to represent the variable geometry introduced by adjustable pitch. The variable then is, quite naturally, the pitch angle, β .

B. Pitch control

With all variable speed wind turbine types, pitch control is an essential feature for operation and modeling.

As the doubly-fed configuration wind turbine is limited with respect to operation speed variability, pitch angle control takes a more complicated role. With this wind turbine type, pitch control is not solely needed for power and speed limitation, but when advantageously executed, it can contribute to energy capture maximization.

The aerodynamic characteristics – i.e., the C_p value - of the rotor, as a function of tip speed ratio λ , and the pitch angle β , must be known for this type of optimization. In the context of control, it is useful to realize that the power coefficient function is a surface in the (C_p, λ, β) -space.

Mullane, Lightbody, Yacamini, and Grimes [58] explain how such surface can be modeled using a Simulink S-Function. Fig. 3 shows a plot of C_p .

There is no simple analytical way of deriving the power curve of the wind turbine from wind speed and rotor data. The wind and rotor data will define the possible limits of power available, but the actual power output will result from the chosen control strategy, and how intelligently it is implemented. The control strategy, in turn, is affected by a complex set of influents, which include considerations of structural strength, dynamic behavior and power quality, among other things. In short, the control strategy is, or should be, tied with the whole design philosophy of the wind power plant.

We do not take a stand on how such a control strategy should

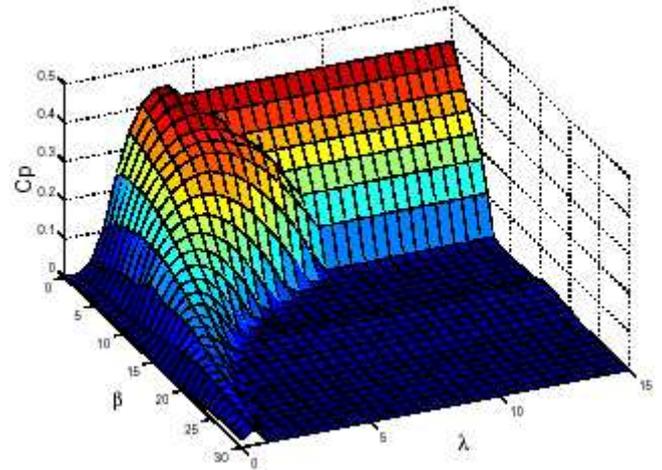


Fig. 3. The power coefficient surface of a wind turbine as a function of the tip speed ratio λ and the pitch angle β . (Adapted from [58].)

be laid out. We merely state that the capability of including the desired control into the simulation tool is essential.

For example, Hansen, Iov, Sørensen, and Blaabjerg [4] discuss the control strategies for the DFIG type machine.

2.3 MECHANICAL SYSTEM

Sørensen *et al.* [59] explain the rationale of choosing a suitable model to represent the mechanical system of the wind turbine.

A rotating non-rigid shaft connecting two bodies with inertia will have eigenfrequency properties. This is the simplest form of wind turbine drivetrain. This type of representation may or may not be considered adequate for power quality simulations. Sørensen *et al.* [61] discuss the merits and disadvantages of varying degrees of detail in the drivetrain dynamics model.

More complex systems will have more complex eigenfrequency properties. Heier [55] (p. 90) lists the periodic and aperiodic processes that are the origin of torque fluctuations within the wind turbine drivetrain system.

The flexible coupling connecting the generator to the gearbox introduces (possibly non-linear) flexibility, and damping to the drive system.

As it happens, the particular simulation program (PSCAD[®]) that we use is quite well equipped to handling the drivetrain dynamics. It is possible to model a six-mass rotating system, that is much more than we expect to need for our purposes, as our main interest lays in power quality issues.

A. Gearbox

When modeling the rotational dynamics, the gearbox can be handled by reducing the shaft stiffness values, as well as the inertia values, to correspond to the speed of the generator shaft or of the wind turbine shaft.

Although undesirable, some slack in the gear drive is almost inevitable. In case of reversal of power flow, this play may cause shock loads. For accurate results, this slack should be represented in the drivetrain model.

B. Tower

The development of the wind turbine evolves towards more efficient use of materials. Consequently, the flexibility of the components tends to increase.

Although easily overlooked, the swaying movement of the flexible tower can actually have an influence on the instantaneous electric output, as reported by Thiringer and Dahlberg, [61].

C. Blades

Because of the trend of lighter construction, more slender and flexible rotor blades are favored. Whereas the aerolastic movements are important with a view to the fatigue life of the rotor, their effect might actually be seen on the electrical variables of the generator, as demonstrated by a simulation model of Larsen, Hansen, and Iov [62].

Meyer [63] presents a reduction methodology for the simulation of the aeroelastic response of wind turbines.

2.4 ELECTRICAL SYSTEM

Compared with fixed speed wind turbines, variable speed configuration turbines involve even more time constants. The complicated electric drive system requires highly sophisticated control, such as vector control.

A. Rotor-side converter

In the stator flux oriented rotor current control the active power and reactive power are decoupled. The rotor side converter controls independently and indirect active and reactive power, by the impressed rotor current as in [4].

B. Grid-side converter

The grid-side converter control aims to maintain dc link capacitor voltage in a set value regardless of the rotor power direction, magnitude, and the power factor at unity. The grid side converter exchanges only active power, and because of that transmission of reactive power from DFIG to the grid is done only through the stator. Dc-link voltage and reactive power are controlled indirectly by controlling the grid side converter current, described in [5].

Other control methods are speed, torque control and direct torque control, ABB [22]. These can also be Digital Signal Processing (DSP) based, presented in [64], with microprocessor control, or fuzzy control. Adjustable current sources are also a model for control of the doubly-fed generator as in [8]. Control may also include circuits for restart of rotor converter and/or soft start to reduce stresses, described in [9].

A runtime simulation of the slip power behavior and the back-to-back converter control, can be modeled in MATLAB[®], DiGSILENT[®], PSCAD[®] etc. as done in [3], [5], [7], [8], [65], [66], [67], [13], and Leonhard [17] 287-306. Modeling in PSCAD[®] is rare, only a very few proposals in this area exist. Thus, comparison between simulation programs have been made, but the differences are small and almost the same results are achieved [59]. The modeling can be done without the transformer, shown in Fig. 1, and the transformer

reduces the dc-link voltage, and the generator winding ratio between stator/rotor can be set to other values than one.

A complete wind turbine system contains subsystems such as, aerodynamical, mechanical and electrical with different ranges of time constants from 0.2 ms to 20 s as in [9]. However, the electric drive requires highly sophisticated control for optimal wind energy conversion and reducing internal losses, described in [7], and [68].

WRIG model is included for example in PSCAD[®], but real parameters have to be known.

C. Crowbar protection

The rotor side converter is bypassed when rotor current exceeds a certain limit, to avoid damage, see Fig. 1, as in [66], by switching the rotor current through a resistor or by blocking rotor side converter by stop switching as in [9]. In this case, grid side converter acts as a static compensator (Statcom).

D. Rotor position

The rotor may or may not have position sensing described in [16]. Sensorless configuration is based on current measurement. In some models, rotor speed is measured and then translated mathematically into rotor angle by integration of rotor speed, ω_r to the rotor side converter, the rotor angle or rotor position is very important, because the angle tells the slip, either positive or negative, and it is fed to the rotor vector controller.

E. Transformer

Fig. 1 shows a three-winding transformer described in [5], which isolates the wind turbine from the grid and its voltage ratio from the generator stator or rotor in proportion to the grid has to be suitable for the specific generator application.

Models are included in some simulation programs and parameters have to be entered including sequence reactances. Transformer models include manual and automatic tap changer with voltage, active or reactive power control. The dc-link voltage can be set to a suitable value by means of this transformer. Harmonics have also to be detected to reduce losses and to prevent damages due to overheat of the transformer.

F. Grid

Disturbances in grid connection are simulated and tested in [26], [9], [67], [60], [23], and [69].

The converter provides reactive power to the DFIG, and the DFIG can produce or absorb an amount of reactive power to or from the grid, and that is important when DFIG is connected to a weak grid and voltage control can be regarded as an advantage. Harmonics in the grid have also an effect on the wind turbine control and efficiency.

G. Compensation

DFIG can produce or absorb an amount of reactive power to or from the grid by means of separate controls for active and reactive power, i.e. the power factor can be set to any desired value by controls. Reactive power can be generated by use of capacitors or capacitor banks, described in [5].

3 OUTLOOK

Simulations with more detail, both mechanical and electrical, have the potential to improve wind energy conversion in the future. Recent developments and future trends in modeling and simulation may include the following topics:

- i* Wind models in complex terrain
- ii* Wind farm modeling, including the effect of wakes on other turbines
- iii* Special topics due to offshore location
- iv* Integration of 3D aerodynamic analysis to global (far-field) modeling Optimal system design
- v* Inclusion of aerolastics effects
- vi* Modeling of noise and vibration
- vii* Use of code-generating systems to produce wind turbine modeling tools, such as described in [70]
- viii* Synchronous control of farms vs. individual control, or more complex control topologies.
- ix* Models for wear because of even longer service life, even 50 years, which means a long time period for spare parts. Reproduced spare parts are to be used (retrofit), as described in [27].
- x* Combination of torque and pitch control to reduce loads.

4 CONCLUSIONS

Modeling and simulation is an appropriate method for studying the effects of power generation of wind turbines to the grid. New models have been developed and implemented in simulation tools. The research is performed in several organizations, and more accurate and powerful simulations tools are running on a PC.

Although a limited field of technology, doubly-fed asynchronous grid-connected wind turbine technology still needs more investigation.

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