Generic models for Wind Power Plants

Needs and previous work

Elforsk rapport 12:47

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Preface

The purpose of this project is to identify needs for standardized generic power system simulation models of wind power plants including their controllers and to identify previous work in the field. The focus is on large wind power plants and their controllability.

The work was carried out by, Lars Lindgren, Jörgen Svensson and Lars Gertmar at Lund University as a project within the Swedish wind energy research program “Vindforsk – III”. This report is the final report for project V-379.

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Comments on the work and the final report have been given by a reference group with the following members: Anders Björck from Elforsk, Urban Axelsson from Vattenfall and Katherine Elkington from Svenska Kraftnät.

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Sammanfattning

Elproduktion från vindkraft ökar snabbt världen över och de enskilda installationerna blir allt större, vilket ökar behovet av lättillgängliga simuleringsmodeller för vindkraftanläggningar. Detta arbete sammanfattar användningen av modeller för vindkraftanläggningar och behovet av standardiserade och generiska modeller. Fokus ligger på styrbarhet av storskaliga vindkraftanläggningar bestående av många vindkraftverk. Det mesta av det tidigare arbetet med standardiserade och generiska modeller har omfattar transient stabilitet och enstaka vindkraftverk. De båda standardiseringsorganisationerna IEC (International Electrotechnical Commission) och IEEE (Institute of Electrical and Electronics Engineers) har pågående arbeten med standardisering av sådana modeller. WECC (Western Electricity Coordinating Council) har tagit fram riktlinjer för modellering av vindkraftsgenerering, vilka har haft stort inflytande.

Vindkraftverk kategoriseras i allmänhet i 4 olika typer. Användbarheten av modellerna avseende övergripande styrbarhet och tillhörande system tjänster utvärderas. Detta görs genom att sammanfatta andra projekt i området och via frågeformulär till några utvalda intressenter i branschen. Svaren på frågeformuläret indikerade ett behov av standardiserade modeller och påpekade vissa svårigheter. Den allmänna slutsatsen är att modeller för vindkraftverk med dubbelmatade asynkrongeneratorer respektive fulleffektsomvandlare kommer att vara de viktigaste typerna att modellera.

Fördelarna med att använda ett generellt modelleringsspråk som t.ex. Modelica beskrivs. De vanligaste komponenterna i modeller av vindkraftanläggningar beskrivs för de olika typerna av vindkraftverk. Aerodynamisk dynamik (”Dynamic inflow”) är troligen ett viktigt fenomen vid modellering av styrbarhet, vilket ofta saknas i vindkraftmodellerna för kraftsystemsstudier.

Definitionen av de olika systemtjänsterna (Ancillary services) och relationen till anslutningsvillkoren diskuteras.

Inga generiska modeller som lämpar sig för modellering av kompletta vindkraftanläggningar och inkluderar både elektriska och aerodynamiska modeller hittades. Sådana modeller behövs för att modellera den överordnade styrningen av stora vindkraftanläggningar och förmågan att leverera olika typer av systemtjänster. Överlag har lite standardiseringsarbete gjorts med avseende på modellering av överordnade styrsystem för vindkraft-anläggningar samt styrbarheten av och interaktioner inom en vindkraftsanläggning.

Summary

Wind power production is increasing fast world wide and the size of individual installations is also increasing, which gives raise to the need for open simulation models of wind power plants. This project reviews the usage of wind power models in the power system and the need for standardized and generic models. The focus of this project is on controllability of large-scale wind power plants including many wind turbines while most of the previous work on standardized and generic models has been on power system stability studies and single wind turbines. The standardization organizations IEC (International Electrotechnical Commission) and IEEE (Institute of Electrical and Electronics Engineers) have ongoing work towards standardization of such models and the guidelines for modeling wind power generation by Western Electricity Coordinating Council have been very influential.

Wind power turbines are generally categorized in four different types. The usefulness of current models with regards to overall controllability and ancillary services were evaluated by summarizing other projects in the area and by collecting questionnaires sent to a few stakeholders in the industry. The answers of the questionnaires indicated a need for standardized models, and pointed out some difficulties. The general consensus was that models for wind power plants based on wind turbines with doubly fed induction generator or full power converters will be the most important models.

The advantages of using a general model specification language such as Modelica are highlighted. The common subcomponents of wind power plant and wind turbine generator models are described for different types. Dynamic inflow, the dynamic response of the aerodynamic system, is found to be a potentially important phenomenon with regards to controllability, but is often neglected in conventional models.

The definition of the different ancillary services and their relation to the grid code is also discussed.

No generic models suitable for modeling controllability of complete wind power plants that include both electric and aerodynamic models were found. Such models would be needed to model plant controllers, which have the ability to provide different combinations of ancillary services. Generally, modeling of plant controllers, controllability and interactions within the wind plant have received very little attention with regard to standardization.

Content

Abbreviations

AB Aktie Bolag, Swedish for Incorporation

ABB ASEA Brown Boveri, an electro technical manufacturer.

ADAMS Automated Dynamic Analysis of Mechanical Systems, a mechanical simulator

AEOLUS An European research project funded by EU-FP7

ARISTO Advanced Real-Time Interactive Simulator for Training and Operation, a power system simulator from Swedish national grid.

ASCII American Standard Code for Information Interchange, a character-encoding scheme

C A programming language

C++ A programming language

CIEE California Institute for Energy and Environment

CIGRE International Council on Large Electric Systems

DFIG/ DFAG Doubly Fed Induction Generator or equivalent Doubly Fed Asynchronous Generator

DSO Distribution System Operator

EC European Commission

ECR EON Climate & Renewables

EDF Électricité de France S.A., an electric utility.

EMC Electro Magnetic Compatibility

EMT Electro Magnetic Transient (simulation)

ENTSO-E European Network of Transmission System Operators for Electricity

EPRI Electric Power Research Institute, Inc, an US based research organization.

EU European Union

EU-FP7 EU Framework Programme 7, a research funding program

FACTS Flexible Alternating Current Transmission System

FAST Fatigue, Aerodynamics, Structures, and Turbulence, an aeroelastic design code for horizontal axis wind turbines

FERC The Federal Energy Regulatory Commission, an US agency.

FMEA Failure Mode and Effects Analysis

FMI Functional Mock-up Interface

FPCWT/FSC/FCWT Full Power Converter Wind Turbine / Full Scale Converter / Full Converter Wind Turbine

GSO Generation System Operator

HVAC High Voltage Alternating Current

HVDC High Voltage Direct Current

IEA	International Energy Agency (or in some contexts Industrial Electrical engineering and Automation, a (sub)department at Lund University)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEEE PES	IEEE Power & Energy Society
MATLAB	MAtrix LABoratory, a numerical computing environment
MEX	MATLAB executable, a type of shared library
NER	Nordic Energy Research
NERC	North American Electric Reliability Corporation
NORDEL	The former organization of Nordic TSOs now part of ENTSO-E
NREL	National Renewable Energy Laboratory, a national laboratory of the U.S. Department of Energy
PCC	Point of Common Coupling
PE	Power Electronics
PLL	Phase Locked Loop
PMSM	Permanent Magnet Synchronous Machine
PMU	Phasor Measurement Unit
PSAT	Power System Analysis Toolbox, an open source MATLAB toolbox
PSCAD/EMTDC	A EMT simulation program
PSCE	IEEE/PES Power Systems Conference & Exposition
PSS/E	Power System Simulator for Engineering
PV	PhotoVoltaic
RMS	Root Mean Square, effective value
SCADA	Supervisory Control and Data Acquisition
SG	Synchronous Generator
SSR	Sub-Synchronous Resonance
TSO	Transmission System Operator
US	United States of America
VAWT	Vertical-Axis Wind Turbine
WECC	Western Electricity Coordinating Council, an organization for western Mexico, US and Canada
WES	Wind Energy Systems
WFMC	Wind Farm Main Controller
WGMG	WECC Wind Generator Modeling Group
WPP	Wind Power Plant
VSC-HVDC	Voltage-Source Converter HVDC
WT	Wind Turbine
WTG	Wind Turbine Generator

1 Introduction

1.1 Background

Power generation started mainly with synchronous generators in power plants. The existing power generation and transmission systems are still mainly equipped with synchronous machines. Wind power production are increasing fast world wide and the individual installations also increases in size. Now the wind turbine generators (WTGs), as singles, clusters and plants, contribute with 3 % energy world-wide—6 % to 30 % nationally in some NW European countries—as part of employing the emerging new-renewable energy sources. This increases the need for different types of simulations of the behavior of wind power plants (WPPs) in the power system. There is very little standardization in the ways to model wind turbines and WPPs in sharp contrast to other electric power generation plants.

- Models for wind turbines have so-far typically been delivered as black box models under non-disclosure agreements.
- Wind power plants have often been modeled by scaling up a wind turbine model to the desired power without taking the wind power plant controller into account.

HVDC transmission is well established and voltage-source-converter (VSC) based converters emerge for cable-transmission from large offshore WPPs. Furthermore, it is natural that there are works that do comparative stability analysis (Muñoz et al 2011) of DFIG-based wind power plants and systems based on conventional synchronous generators (SGs) where generic models were established a generation of power engineering professionals ago when power transmission system simulations emerged. Regarding the future offshore, grid-connection of large offshore WPPs utilizing VSC-HVDC are modeled and studied what regards grid impact (Xue 2009 et al).

- Our focus in V-379 is to give background for Vindforsk's and its stakeholders' future R&D on more than type 3 (DFIG) wind turbine generators aiming at multi-applicable generic models for WTGs to cover the need for standardization of wind power plant models for stability studies (Persson et al 2009).

1.2 Generic models

Generic WPP models are models that are parameterized in such a way that they can represent a wide range of WPPs reasonably well.

Generic models are normally not able to capture all aspects of a WPP as good as a purpose built WTG or WPP specific model. Manufacturer specific models will probably still be needed for example in order to check the performance as a step to verify a WPP's compatibility with grid-codes.

Widely available generic WPP models make it easier to model WPPs before the actual design of the WPP is decided. It also make it a lot easier to build and handle dynamic power system models as compared to specific proprietary WPP models under non disclosure agreements for each WPP.

It is preferable if the models are standardized either as formal standards or de facto standard in order to simplify comparison between different studies. Standardized models also make it a lot easier to translate power system models of WTGs/WPPs between different simulation tools.

1.3 Previous and ongoing work

Much work such as the WECC modeling guidelines and the following IEEE and IEC standardization efforts focus on the response of single wind turbines to grid disturbances. Completed WTG generic models of single wind turbine generators were approved in the WECC work and implemented as standard-library models in PSSE 32 and in (GE)PSLF 17.

Plant controllers, controllability and interactions within the wind plant have got very little standardization work.

1.4 Scope

The focus of the reported work is on simulation, control and controllability of large-scale (> 100 MW) WPPs in the timescales 5 ms to 1000 s. Generic models for shorter integration time steps down to 0.01 ms could also be of interest.

Since the models should be used to study the control of WPPs at different levels, generic models need to include some standard controllers and have a structure such that it is possible to replace existing controllers or add new ones in a realistic way. As most new large wind turbines have variable shaft-speed and blade-pitch control the work focuses are on these.

As WPPs include many wind turbines with individual and autonomous wind turbine control, the functions of plant controllers managing the coordination of the wind turbines becomes more important. This is essential in order to coordinate wind power at power system level, but also optimizing the balance between generation and maintenance within WPPs.

1.5 Objectives

The objective of this project is to identify needs for standardized generic power system simulation models of wind power plants including their controllers and to identify previous works in the field. The focus is on large WPPs and their controllability.

1.6 Outline

Chapter 1 Introduction (this section) comprises the purpose and scope for this report as well as some terms, abbreviations and acronyms used while most of these are introduced where they are used in the chapters that follow.

Chapter 2 gives an overview of wind power plants, different control modes and Ancillary services.

Chapter 3 gives an overview of how wind power plants can be modeled for different needs.

Chapter 5 summarizes some previous and ongoing projects.

Chapter 6 summarizes the replies from the respondents to a questionnaire to a few stakeholders in the industry.

Chapter 7 summarizes chapter 1-6.

Chapter 8 suggests future work based on these findings.

2 Wind power plant overview

2.1 Introduction

Wind power has been, and still is, a very small part of the total power generation worldwide. However, the yearly expansion in wind power is currently the largest in the energy business sector. The national goal for many countries is a substantial increase of renewable energy within the next decade that has influenced the market rapidly. The number of wind turbine suppliers is still increasing and will offer strong competition conditions on the market.

The capacity of individual WPPs has increased dramatically over the last decade. Ten years ago a few WPPs were built with a capacity around 100 MW and in 2010 the capacity was typical 200 MW. The largest ongoing projects today are in the range of 400-600 MW (e.g. Anholt and London Array). There are plans for several >1000 MW of capacity WPPs the next years to come. Most of the large-scale WPPs expansion will likely happen offshore, but also a substantial number of WPPs are also planned onshore.

The expansion will gradually affect the power systems. The grid codes and the possibilities for WPPs to supply ancillary services will become very important. The capacity and controllability of future WPPs will be very much dependent on the wind turbine, collection grid and nearby transmission technologies.

2.2 Wind turbine technology

The nominal power rating of typical wind turbines today is 2-3 MW onshore and 3-5 MW offshore. Some suppliers can now also offer wind turbines in the range of 6-7 MW. The layouts and designs of wind turbines employ standard components and well-known technology for all the important functions.

However the technologies still vary much dependent on wind turbine supplier. The reasons are sometimes historical, but mostly related to the time to introduce and utilize new technology on large scale depending on maturity and life-cycle costs.

Historically, the older wind turbines were directly connected to the grid (Figure 1a) and had more or less constant speed, which is mechanically inefficient. The most used design the latest decade is shown in Figure 1b, the double feed induction generator (DFIG) with variable speed, which enables both active and reactive power control. Many suppliers still use this design.

In Figure 1c, the direct connected (gearless) full converter solution is shown, which is becoming more commonly used among suppliers from now on. In this example, the electrical system includes a permanent magnet synchronous machine (PMSM), the converter and transformer. As the converter includes a DC-link, the generator is completely decoupled from the grid. The converter can be used for controlling the active and reactive power independently and controllability is consequently very high.

The fourth solution shown in Figure 1d is basically the same as in Figure 1c except for the gearbox enabling the use of traditional high speed generators. This solution means smaller generators and lower weight even when the gearbox included as a weight. The disadvantages are another component decreasing the reliability of the power unit and also the fact that the gearbox, so far, is a highly failure rated component. This design seems to be a transition solution from design 1a to 1c for some suppliers in order to test and learn. However, depending on the progress in gear technology, design 1d might turn out to be a strong alternative.

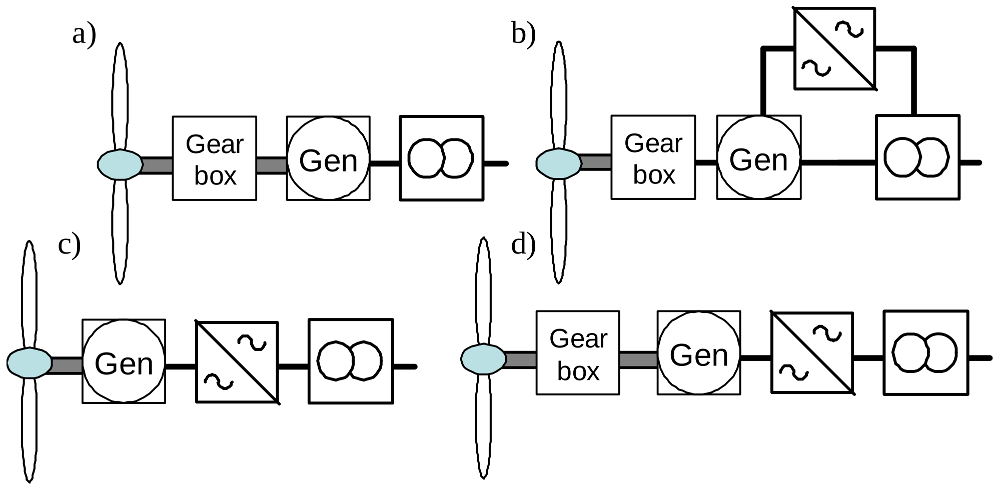

Figure 1: Wind turbine (drive train) technology

In summary, the trend in wind power design is an amplified use of converter technology and also full power converters with high controllability. Future wind turbine design will most likely be based on as few components as possible, for availability reasons, and with high controllability enabling several services to the grid such as power-, voltage, and frequency-control. The wind turbine power rating will then only be limited by the logistic and mechanical conditions/limits. For these reasons and the belief in future wind turbines in the range of 10-20 MW per unit could lead to alternative design such as the vertical axis wind turbine (VAWT).

2.3 Wind power plant design

Traditionally WPPs are designed based on several radials of wind turbines connected to a substation (transformer station). For larger WPPs, the power plant may be divided into subsystems in a modular structure as shown in Figure 2. This is already applied on some large-scale WPPs as Rödsand 2 and Horns Rev 2, where the internal electrical system is divided in two identical subsystems. These have consequentially two overall superior controller systems, i.e. sub plant controllers.

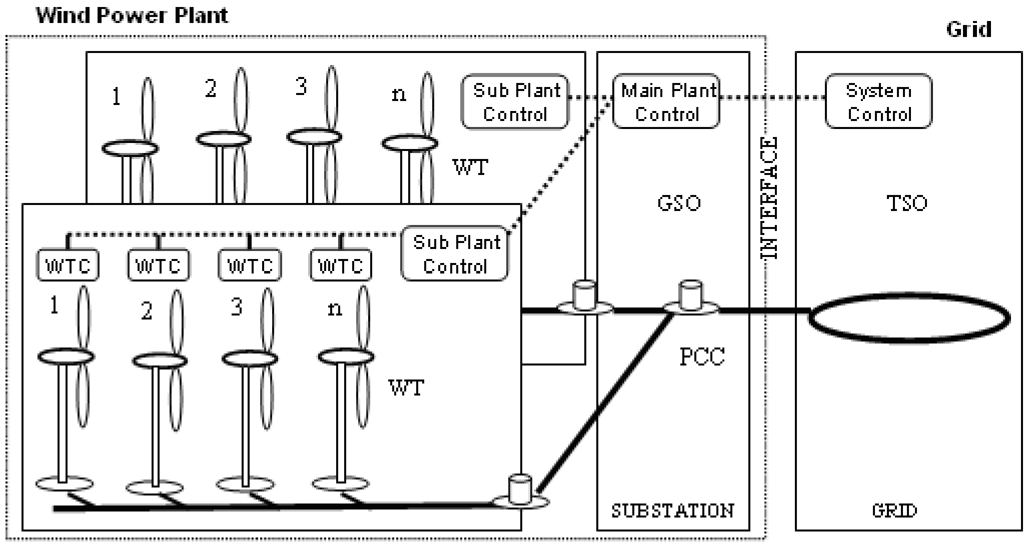

Figure 2: Wind power plant structure

Briefly a WPP (or subunit) may include the following parts:

- *Wind Turbines* (WT) including foundations that are in the range of 3-7 MW. Dependent on location, the next generation of wind turbines will be in the range on 6-10 MW (primarily offshore). Independent of supplier, WTs will have power converters in the range of 30-100 %. The WT units are able to work autonomously or operated by superior control-levels.
- *Internal transmission networks* are still based on AC but may also be based on DC in short future. The WTs are normally connected in parallel along the cable sections as radials. This may vary strongly upon design and optimizations criteria's. The communication lines are normally internally connected along the power cables with integrated fiber cables.
- *Substations (transformer- or converter-stations)* raise the internal voltage from medium voltage e.g. 22 kV or 33 kV to high voltage 130 kV or higher (AC or DC) dependent on the capacity of transmission cable. The converter substation enables high controllability and simpler means for disconnecting as well as being autonomous. For redundancy reason, it is appropriate with 2-3 such units in parallel permitting the WPP to produce at partly capacity in case of failure.
- *External transmission network*; Large WPPs are today connected directly to onshore at 100-150 kVAC, but may also be connected to a multi-drop HVDC (high voltage direct current) transmission system in the range of multiples of 100kVDC or interconnecting several onshore regions or nations.
- *Distributed Automation* includes the information system within a WPP that interconnects each individual wind turbine control system to the main plant control (or via sub plant control if using sub WPPs). The plant control of the WPP internally manages and operates all the wind turbines and externally acts as one power generation unit. The main plant controller act

as an interface in-between an external system control operated by a TSO (transmission system operator) and all individual wind turbines operated by the GSO (generation system operator).

- *Point of common coupling (PCC);* is the connecting point where the electricity produced is supplied to the public electricity supply grid (or future offshore power system). The location of the PCC can vary depending on owner responsibilities and grid requirements. The PCC is normally considered as the interface between the power plant and the grid where the requirements apply and are validated. The requirements are related to grid codes and ancillary services.

The internal WPP structure will vary over time depending on economic optimisation based on availability and controllability constrains as a consequent from grid requirements. This will also have a continuous effect on the technology development for years to come.

2.4 Operation and Interaction

The expansion of large-scale WPPs raises new issues concerning operational methods. Traditionally a WPP is controlled in order to produce as much power as possible. As part of a WPP, the wind turbine control has to be supervised from a higher level. Since WPPs tend towards capacities of several hundreds of MW, they must be considered as large-scale controllable generating units, in a similar way as hydro- or nuclear power plants. The major difference is the fluctuations and the large number of generating units (wind turbines) to be coordinated inside the WPP. This requires a supervisory controller, here called the "plant controller" (in some literature named "wind farm main controller", WFMC), as an interface in between the transmission operational system and the wind turbine units of the WPP. The plant controller is responsible for coordination and scheduling methods for operating the WPP and its sub-plant WTG units optimally even in a limited output power mode.

The operation of a WPP differs from a common generating unit primarily in power fluctuation due to the wind. A WPP is therefore regarded as a stochastic generating unit that demands accurate power measurements and reliable maximum power estimations to provide the Generation System Operator (GSO) and the TSO with correct real–time information for decision-making.

Nearby offshore WPPs under construction are able to participate in both primary and secondary control. The controllability is dependent on WT and WPP design. Most of the new large-scale WPPs today are able to provide ancillary services. In ongoing project for large offshore WPPs massive effort is currently dedicated to investigate the possibilities of additional control modes and on how to implement them.

The goals of the GSO and TSO may differ depending on WPP usage and the interaction in-between the GSO and TSO:

- The main goal for the GSO is to operate the WPP in maximised generation with as low wear and tear of individual wind turbines as possible. The same applies when an external control mode is activated, such as from the TSO or DSO (distribution system operator). This means that many different coordination methods could be performed to maintain the control mode and still avoid too much wear and tear. How the internal coordination is performed is usually not a matter for the TSO or DSO as long as the grid codes are met.

- The main goal for the TSO is to be able to change control modes of the WPP depending on power system status in order to solve or prevent critical operation situations. Before even developing and going into operation a planning study needs to be performed by the TSO. These needs will increase over time as the share of new renewable energy sources increase and synchronous-machine inertia decreases.

Related to development of new equipment and functions are several sub-contractors and technical consultants pre-testing different components and/or the entire WPP.

A common goal for all engaged is to analyse and test sufficiently before developing and constructing a new hundreds of MW WPP in order to meet all internal and external requirements. A common platform including specifications on models and ancillary services are essential for such analyses and pre-test.

2.5 Ancillary services

Ancillary services are services that for example a WPP can deliver to the grid in addition to its main service, the energy delivery, from the WPP.

Ancillary services can include a very wide array of services that are needed to reliably transfer active power in transmission and distribution systems. The number of different ancillary services can be in the range of 6 to 40 different services depending on definitions used (Hirst et al 1996).

Five glossary definitions:

> "(system) ancillary services
> services necessary for the operation of an electric power system provided by the system operator and/or by power system users. NOTE – System ancillary services may include the participation in frequency regulation, reactive power regulation, active power reservation, etc." (IEC 600 50, 2009)

> "FERC defined ancillary services as those 'necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.' "(Hirst et al 1996)

> "Any service required by a system operator to deliver electricity to the ultimate consumer. Ancillary services include balancing services, load following, or providing kilovars (reactive power)." (Platts 2012)

> "The system operator contracts individual participants to provide five services essential to maintaining the common quality of electricity supply, these ancillary services are black start, over frequency reserve, frequency keeping reserve, instantaneous reserve and voltage support." (EA 2012)

> "Ancillary services are defined as all those activities on the interconnected grid that are necessary to support the transmission of power while maintaining reliable operation and ensuring the required degree of quality and safety. There are several activities of the operator that come under the preview of ancillary services. The definitions of some services and distinctions between some of them are often unclear." (Zhong 2003)

Some ability to supply ancillary services are often required in the grid code other ancillary services can be traded separately.

Ancillary services can be categorized in different ways; most of them are basically the ability to control the active or reactive power in different ways. An ancillary service can either be a guaranteed capability to be able to take some actions if needed during a specified time frame or it can be services traded when needed. One complicating factor are that many WPPs can only produce ancillary services when the wind is strong enough to keep them in operation, some wind turbines can give reactive support even with no wind.

2.5.1 Active Power control

WPPs can rather easily be made able to lower the production when needed. Some services could be:

- Down-regulation, ability to—within specified time after a signal is received—lower the active production by a certain amount.
- Up-regulation, ability to—within specified time after a signal is received—increase the active production by a certain amount. Requires the wind power plant to operate below the available power most of the time and thereby with lower active production.
- Active power ramp limits, limits the rate of change of the active production, limits to the rate of increase are rather easy while limits to the rate of decrease require that the active production is limited below the currently available power according to fastest possible forecasted drop in available wind power.
- Frequency control, the active power is automatically adjusted to try to keep the nominal frequency that requires fast response. Normally some of the available power needs to be reserved so that the power can be increased. (Mehmedovic 2012)

- Inertia (simulated). It is desirable to slow down the rate of change of the frequency in response to an unbalance in the system. Normally the rotating masses of directly connected synchronous machines provide this service due to the inertia in the rotors and prime mover. Wind turbines with variable speed do not provide this service without a separate controller that simulates inertia. The real inertia of the wind turbine is used as the energy storage. (Björnsted 2012)
- Damping of power oscillations. Power system oscillations can be damped both by modulating the active or reactive power of the wind power plant, normally modulation of active power are most effective. (Elkington 2012)

2.5.2 Reactive Power control

Modern wind power plants have good ability to quickly control reactive power. The reactive power capability of a wind turbine with full scale power converter is limited by the maximum converter current and will therefore depend on the instantaneous values of the local voltage and the active power produced. In a DFIG, the reactive capability will also depend on the actual turbine speed. Some wind power plants will have separate equipment, e.g., FACTS devices, for reactive power compensation that can add to the capability. The reactive consumption or production of the collection grid must be taken in to account. For wind power plants connected through a HVDC-link the reactive capability will be determined only by the HVDC-converter.

There are several modes for reactive power control:

- Reactive power set point, the desired reactive power is given directly.
- Power factor control, the desired ratio between active and reactive power are given.
- Voltage control, the wind power plant tries, by adjusting the reactive power, to keep the voltage at an arbitrarily chosen point in the system, normally the local voltage close to a given set point.

Traditionally voltage control has been avoided in wind power plants since it increases the probability that an unintended island situation will be stable. This could be dangerous if the system is not designed and commissioned to handle the situation.

2.5.3 Others / combined

There are also other ancillary services that are not purely dealing with active and reactive power such as black start capability, ability to restart production shortly after a blackout and supply of short circuit current to help the system maintain synchronism during a remote short circuit fault. Other possible services found are active cancellation of harmonics and asymmetry in the system voltage.

2.6 Control modes

WPPs can be operated in different control modes both regarding active power and reactive power. Normally, active power has priority when the combination of active and reactive power reaches the limit of the converter.

2.6.1 Active power

The control modes of a WPP correspond rather closely to the ancillary services provided.

- Maximum production, this is the normal operating mode, the production is kept as high as possible given the instantaneous wind speed and the ratings of the wind turbines.
- Fixed maximum output, the output are limited at some level below the rated power and are kept at this level or lower depending on wind. Could for example be used when the transfer capacity from the WPP are limited. Could also be used when selling down regulation.
- Delta control, the output power is kept lower than the current wind situation would allow in order keeping a specified margin so that the power can be up-regulated if needed. This can be used to provide spinning reserve and to trade up- and down-regulation.
- Frequency control, the WPP regulates the active power output to keep the frequency close to the nominal value. The ability to regulate down the power at high frequency has a low cost when the frequency are close to nominal while the ability to regulate up the power when the frequency are low has a rather high cost since the wind power plant will operate below its maximum production for long periods.

2.6.2 Reactive power

Some WPPs are able to supply reactive power even when the active power production is shutdown due to low wind, other ones are not. The control modes correspond directly to the ancillary services provided.

2.7 Requirements on controllability

The controllability demands on future large WPPs will likely be higher than for conventional units today. If the power system has a large proportion of stochastically generating units such as wind power, this might decrease system stability. However, if following the long-term plan of national goals for expansion of wind power, this should be realized at an early stage.

Considerations due to the impact on the transmission network lead to more specific requirements towards the wind turbine manufacturers, operators and utilities. It is not only the functions within the WPP that will be affected when the impact on transmission network must be better controlled. The safety margins and reliability for existing power systems decrease as a consequence of the increasing the share of installed WPPs. This raises new requirements on controllability and on which type of ancillary services to be available for the

TSO. As the distribution grid becomes more active the distribution system operators (DSO) will increase their requirements on the wind power generators, clusters and plants in a similar way.

Denmark has so far the most large-scale WPPs and also high requirements on grid codes and ancillary services. As a part of the requirements before permitting a WPP to operate a simulation model and simulation results must be provided in order to test the performance and grid codes of the WPP. This is later validated when the WPP is in operation. Some other nations are in similar situation as Denmark and others will follow. Overall, the requirements on grid codes and ancillary services will be updated and reconsidered as the share of wind power increases.

2.8 Requirements on simulation models

An essential part of the commissioning is preparing operational analysis of WPPs to test existing requirements on grid codes. In Denmark these tests are performed by Energinet.dk (TSO) where dynamic simulations are a part of the requirements for approval of WPPs to be connected and operated. A common problem for a WPP developer or owner is often that the models derived from wind turbine supplier are so called "black box" models, which do not provide all necessary information and can not be adjusted or developed. Open-models for operation and control of the entire WPP with interface to the TSO that allows for external operation (control) are almost absent today and are regarded as a related need.

Another area which has special requirements is the large scale expansion of offshore WPPs that will create new offshore power systems based on multi-terminal HVDC and high impact on converter technology. These new systems are already in strong need for model development and system analysis via simulations.

As a consequence many companies and research groups develop their own models in order to analyze WPPs. This means that numerous islands of model developers exist using different models and model implementations and in multiple timescales dependent on application. This also gives very different analysis results, some more accurate and some less.

Consequently an important issue regarding models and validation is the access of open (generic) dynamic models and its implementation. Several organizations have ongoing work towards a “model standardization” and a “common platform” for all to be used as described in chapter 5. Yet, there is a long way ahead before reaching that goal.

3 Model requirements

3.1 Usage and needs

The need to include WPPs in power system simulations constantly increases. The requirements on WPPs to support and stabilize the system also increase; these can have two different forms:

- Grid codes that the WPP needs to fulfill in order to be allowed to connect to the power system.
- Additional ancillary services that are traded separately by the wind power plant operator.

Transmission system operators need to have simple standardized models to use in simulations of the power system as a whole; such models are available for most other components in the power system.

These models will also be useful for the WPP owner and distribution system operator (DSO).

Simple and realistic models are also useful for the academic research community.

The focus in this report is on models that show the external controllability of the WPP. This includes the plant controller and how different wind turbines in a WPP may be operated in different modes.

3.2 Timescales and simulation modes

Power system simulations and simulation models can be made on many different levels.

Simulations can be categorized according to different criteria: time-scales, time-domain vs. frequency domain and other assumptions.

Simulation models with small step size and many details are less useful for large scale long term simulations since it is hard to get all the data and the simulation times become to high.

Some common simulation types or analysis types in power systems are:

- Static power flow, a specific load situation are calculated in steady state. Can also include calculation of different stability limits. Normally three phase symmetry and fundamental frequency only are assumed.
- Repeated power flows, can include slow load dynamics, frequency control and variations in load and production. Step sizes in the range of 1 second to 1 hour. Normally three phase symmetry and fundamental frequency only are assumed.
- Short circuit analysis, simplified static analysis of the fault currents and voltages a few periods of the fundamental frequency after a short circuit fault has occurred. Includes non-symmetric fundamental

frequency calculations. Used for checking relay protections and the maximum short circuit current the components needs to withstand.

- Electromechanical transient simulations, (also called symmetric RMS-value simulation or phasor simulation) includes the dynamic from the rotor angle and speed in electrical machines and the electromagnetic dynamics of the rotors while the electromagnetic dynamics in the electrical network are assumed to operate in steady state. Only three phase symmetric fundamental frequency are modeled. Step sizes in the range of 1 millisecond to 50 milliseconds.
- Electromagnetic circuit simulation, instantaneous values, with lumped components. The instantaneous values for the voltage and current in each phase are calculated. Power electronic converters can be modeled with all the switching events or they can be modeled as current sources or voltage sources. Step sizes in the range of 0.1 micro second to 1 millisecond. Normally only a small part of a power system is simulated at this level.
- Electromagnetic wave propagation, simulates lines as a continuum with wave propagation. Used for insulation coordination. Step sizes in the range of 10 nanoseconds to 1 microsecond. Normally only a small part of a power system is simulated at this level.

Most generic wind power models are for electro-mechanical transient simulations and these are the focus in this report.

Response time to external control signals will normally be at timescales that can be modeled by such models.

Instantaneous value simulations are some times needed to model the response to short circuits faults close to the WPP’s connection point. It is probably also necessary to model the interaction between the plant and the adjacent system parts.

3.3 Turbine types

The WECC “Wind Power Plant Dynamic Modeling Guide” (WECC 2010), defines four main types of wind turbines. This report will use the same classification.

The same classifications are also used in the draft of IEC 61400-27-1. The types are:

1. Fixed speed squirrel cage induction generator, 1a are turbines without blade angle control and 1b are turbines with blade angle control. These wind turbines was common in earlier installations but are uncommon in modern large scale installations.
2. Wound rotor asynchronous generator with controllable rotor resistance and blade angle. These are also rather uncommon in modern large scale installation. The controllable rotor resistance allow some control over the speed by vary the slip. This gives higher looses but can reduce the mechanical stress due to wind gusts.
3. DFIG turbines with pitch control. This type of wind turbine has a wound rotor induction machine with the rotor winding connected via slip-rings

to an electronic power converter. The speed of the rotor can be varied in a limited range around the synchronous speed.

4. Full power converter and pitch control. These wind turbines have an electronic power converter between the generator and the grid. The converter needs to be rated for the full power hence the name. The speed range of the turbine is completely independent of the grid frequency.

3.4 Sub models

A WPP model has a lot of sub models for different components and phenomena. The modeling of each depends on the type of wind turbine and the intended usage of the model. The models will be described roughly in the order from the wind towards the power system.

3.4.1 Wind model

To model the expected wind speed and variation at a geographical location requires meteorological models of the weather patterns in the area. They are normally calibrated against local measurements

Modeling of the undisturbed wind is not included in this report, measurement series could be used if available. Wind variations and wind gusts do not affect the whole WPP simultaneously so for some studies it may be necessary to model both temporal and spatial variations.

3.4.2 Aerodynamics

The aerodynamic behavior is often modeled by a simple stateless static model.

$$P_{mec} = \frac{A\rho v^3 C_p(\lambda, \beta)}{2}$$

Where (A) is the swept area, (ρ) is air density, (v) is the wind speed, ($C_p(\lambda, \beta)$) is the proportion of wind energy that is extracted, as a function of λ the ratio between the tip speed of the wings and the wind speed β is the pitch angle of the blades. $C_p(\lambda, \beta)$ is often modeled as a lookup table. Some time the aerodynamic power is modeled simply as constant power or constant torque.

The wind speed through a wind turbine is lower than the undisturbed wind speed. This difference depends on the extracted power, if the extracted power is changed, for example by changing the pitch angle, it will take some time before a new steady state speed is reached due to the inertia of the air. The change in kinetic energy of the air can be larger than the kinetic energy in the rotating parts of the wind turbine. The dynamic inflow phenomena can be approximated by a simple lead-lag filter but the time constants are highly dependant on the wind speed. Typical time constants are about 10 seconds (Perdana 2008, Anaya-Lara 2009).

For power system stability studies it is generally considered enough to use the stateless model. (Perdana 2008)

On the other hand some simulations (Ackermann, editor, 2005, page 616) indicate that dynamic inflow can make a big difference.

For modeling the active power controllability on timescales between 0.5 s to 100 s, it may be necessary to model the dynamic inflow phenomena.

The reason modeling of dynamic inflow does not seem to be needed in power system stability studies is probably that these generally consider the capability to reduce mechanical power and the pitch controller corrects for the differences between the models. Therefore dynamic inflow is probably more important when power should be increased quickly.

There are also other dynamic effects such as the elastic deformation of the blades and so on for power system studies this is normally disregarded.

The extracted power can be controlled in two different ways (Ackermann, editor, 2005):

- Active pitch control, mainly used in turbine type 2, 3 and 4. To lower the extracted power the pitch angle is increased above the optimum so that the blades are more in line with the wind.
- Active stall control, mainly used in turbine type 1. To lower the extracted power the pitch angle is decreased below the optimum so that the blades stall due to the high angle between the blades and the wind.

3.4.3 Wake effect

Each wind turbine creates a wake with lower wind speeds behind it. The amplitude and size of the wake depends of the power extracted by the wind turbine. Changes in the wind speed travel downwind approximately at the wind speed (Grunnet et al 2010). This gives dynamic behavior in the WPP in the range from 15 seconds to 15 minutes depending wind speed and the geographical layout. The wake effect is very complex. It has been studied with detailed aerodynamic simulations but such models are too complex and computationally expensive to include in generic WPP models for power system simulations.

3.4.4 Mechanical system

The mechanical system of a wind turbine has many different resonance modes due to the component elasticity and their masses. For power system studies, it is normally enough to consider a highly simplified model of the mechanical transmission.

The mechanical transmission of a wind turbine is usually modeled with 1, 2 or 3 rotating masses. The masses of the three-mass-model are normally:

- The outer parts of the blades.
- The inner part of the blades and the hub
- The rotor of the generator.

The masses are coupled by springs and with damping.

In turbines of type 1 and 2 the oscillation modes of the mechanical system are directly coupled with the electro-mechanical oscillation modes in the power grid.

In turbines of type 4 and to some extent 3 the grid is more isolated from the mechanical system due to the power electronic converters and the control system. So, it is common to model the mechanical system as only one mass. Controllers that for example damp mechanical oscillations or power system oscillations by modulating the generator toque may reintroduce a coupling.

3.4.5 Generator

The type of generator differs between the different types of wind turbines. The generator model is most important in wind turbines of type 1 and 2. In wind turbines of type 4 the generator dynamic is almost isolated from the grid and is often modeled very simply in power system simulations.

- Type 1 has a squirrel cage induction generator directly connected to the grid. Often modeled with a third order model (rotor flux in d- and q- axis and rotor speed). Stator flux dynamics normally omitted. Since the generator is directly connected to the grid the generator model are very important in power system simulations.
- Type 2 has a wound rotor induction machine. The winding is connected to a electronically controlled resistor. Can be modeled as type 1 but with variable rotor resistance.
- Type 3 has a doubly fed induction generator. This is a wound rotor induction machine that is connected so that it can transfer active power through both the rotor and stator winding. The rotor winding is via slip-rings connected to a power electronic frequency converter that has a rating of about 30 % of the total power rating of the wind turbine. In normal operation the active and reactive power of the turbine can be controlled quickly and independently by the converter and the generator model is therefore not as important for power system simulation but in the case of large disturbances on the grid the converter is turned off and resistors, called crowbar, are inserted into the rotor circuit to limit the voltage. The generator then behaves as a normal induction machine with high rotor resistance.
- Type 4 can have a permanent magnetic synchronous generator, an electrically magnetized generator or an induction generator. The generator is separated from the grid by a power electronic converter and the generator model can therefore be very simple for most studies.

3.4.6 Converters

Converters, based on power electronic circuits and controllers, are used in wind turbines of type 3 and 4. The converters are composed of a grid side controlled three phase bridge, a generator side controlled three phase bridge and a DC-link, which is composed of a capacitor.

The controller can be modeled in many different ways. The simplest way is to model it as controllable active and reactive current on the grid side with the condition that the active power in and out should be balanced. The energy stored in the capacitor can be neglected in most cases. The total current and voltage need to be within set limits, which give a capability in the PQ-plane that is a circle around origin whit a radius dependant on voltage. In simple models of type 4 wind turbines, the active power can just be taken as the mechanical power of the turbine.

In electro-magnetic circuit simulations, the converter can be represented as a controllable voltage source per phase, a controllable current source per phase or it can be modeled with all the switching events in the bridge depending on the level of detail needed. Depending on the application, different models are needed ranging from microseconds to seconds.

3.4.7 Turbine controllers

The wind turbine controller includes many controllers, such as pitch control, speed control and reactive power control. Ancillary services should be implemented dependent on technology and requirements. If the WPP supplies ancillary services, the control of these can be implemented in the turbine controller, plant controller or in both.

The modeling of these controllers depends on the type of simulation and the purpose of the simulation. In the case of three phase symmetric fundamental frequency simulations the controllers for converters need to be converted to work with phasors in stead of instantaneous values. Depending on the integration time step some fast control loops may need to be converted to algebraic equations.

Normally the pitch is kept constant in low wind speeds and in variable speed turbines the turbine speed is controlled by adjusting the pitch angle.

3.4.8 Plant controller

The plant controller tries to minimize wear and tear on the equipment while supplying the requested active power and other ancillary services. The division of the production between the different wind turbines affects the controllability of the plant. If the active power is limited by turning of wind turbines the fast controllability is reduced.

The plant controller also manages the external control signals from the TSO, DSO and GSO. These signals are determined and further distributed in the WPP dependent on requested control mode.

3.4.9 Internal grid

The internal grid in a WPP normally consists of medium voltage cables. If the wind turbines are modeled as individual units then the internal grid can be modeled as any other medium voltage grid in the chosen simulation tool.

3.4.10 Protection system

Just as the controllers the models of the protection system must be adapted to the type of simulation.

3.4.11 Grid connection

The distance from the WPP to a suitable connection point in the existing grid can vary a lot. Large WPPs generally need to connect to the sub-transmission grid or even to the transmission grid. High voltage AC lines are normally used to connect a WPP to the grid. A HVAC grid connection can be modeled as any other HVAC line.

The main reason for using HVDC connections is the limited length of submarine HVAC cables due to the high capacitive current. There are however also other advantages such as the possibility to improve the low voltage ride through capability of the WPP. HVDC transmission is a well established technology. In wind power applications, it is mainly voltage-source-converter (VSC) based systems that emerge as a solution for cable-transmission from large offshore WPPs.

A HVDC connection have a great impact on the behavior of the WPP since it separates the reactive power in the WPPs internal grid from the external grid so they can be controlled separately on this aspect.

An HVAC grid connection of a WPP can also include equipment for e.g. reactive compensation, voltage control and filters for harmonics. Just as the HVDC-link it self these components are not unique for WPPs. Therefore, the modeling of this equipment is rather well studied. If the equipment is controlled by the plant controller this control needs also to be modeled.

4 Simulation platforms (tools)

4.1 Background

For the development of generic models of WPPs and their use, there is a need for modeling complex power system components in different simulation tools. This is an issue, even if using a model standard specification, as equations are implanted in various ways in different simulation tools and they may have different solvers. Further, the users have various requests on application and time-scales and consequently several simulation tools.

4.2 Simulation tools

A selection of the available tools used in wind modeling are described here, these includes both generic simulation platforms and specialized power system simulators.

4.2.1 MATLAB/Simulink

MATLAB is a generic software package/programming environment for numerical calculations from MathWorks. Simulink is an add-on to MATLAB for simulating dynamic models that are created by drawing block schematics. MATLAB and Simulink are widely used to model almost all kinds of dynamic systems. WPPs and WTGs can be modeled directly but often it is convenient to use a specialized toolbox for power system simulation. Simulink can under certain conditions export models as C-code that can be interfaced with many different power system simulators such as PSS/E and DIgSILENT.

SimPowerSystems

SimPowerSystems is a blockset to Simulink for modeling different circuits including electric drives, power systems and generation. It is developed by MatWorcs just as Simulink. It includes some models for wind power and the flexibility of Simulink makes it easy to add more. SimPowerSystems support static power flow calculation, phasor simulation and instantaneous value simulation.

PSAT

Power System Analysis Toolbox (PSAT) is an open source toolbox for MATLAB/Simulink, for power flow and phasor simulation. It also has a limited support for running in the open source environment Octave instead of MATLAB. It is written in MATLAB and uses Simulink as a graphical editor only.

It was written by prof. Milano et al. at Power & Energy Systems Group, University of Waterloo (Milano 2010). It includes wind power models.

After ten year of experience developing PSAT, Power & Energy Systems Group at the University of Waterloo with prof. Milano et al. restarted from scratch and is creating a new software project for power system analysis. The name of this work in progress is Dome. This project is written in Python, C and Fortran. It is not open source.

4.2.2 PSS/E

PSS/E is a power system simulator from Siemens and is part of the Power System Simulator PSS Product Suite.

For transmission system analysis and planning, PSS/E is very widely used. It includes power flow calculation and phasor simulation, and is known to handle very big power system well. It has probabilistic analyses, optimization and advanced dynamics modeling capabilities.

The latest version, version 33, includes implementations of both the IEC WTG models and the WECC WTG models as described in the next chapter (Lin 2011) (Kazachkov et al 2011).

PSS/E is well established for developing and using generic wind turbine generator models whereby WPPs—for simplicity—often are modeled via aggregation with neglected collection cabling.

4.2.3 PSS/NETOMAC

PSS/NETOMAC is a network planning tool owned by Siemens and is part of the Power System Simulator PSS Product Suite just as PSS/E.

NETOMAC stands for NEtwork TOrsion MAchine **C**ontrol

It can work with both time domain simulations and frequency domain calculations such as eigenvalue and eigenvector calculations.

Both simulations with instantaneous values and fundamental frequency simulations are possible. Parallel simulations where part of the system is simulated as instantaneous value simulation and the rest are simulated with fundamental frequency only are possible. The simulation mode can also change during the simulation.

It has also many other capabilities such as:

- Power Flow Mode
- Short Circuit Mode (IEC / ANSI)
- Network reduction
- Interactive network training simulator, Real-time simulation
- Real-time capability for protection testing, network security calculations
- Parameter optimization routines

4.2.4 Simpow

Simpow is a power system simulator developed originally by ABB. It was bought by STRI AB 2004 and in 2011 it was bought by Manitoba Hydro International. It has been heavily used in HVDC development.

It supports power flow, symmetric/unsymmetrical phasor simulation and instantaneous value simulation. Different part of the model can use different simulation modes and the simulation mode can be changed during the simulation. Frequency domain analyses are also possible.

Is has its own modeling language, DSL, for user defined models.

Highlights in Simpow v11.0 (http://simpow.com/software.html) comprise:

• Full Power Converter Wind Turbine, i.e., IEC type 4

• HVDC Light Open Model Version 1.1.6

IEC type 3 was not found during the V-379 work as an open model in Simpow.

"Design and dynamic performance of wind parks in a power system taking advantage of HVDC Light® as system stabilizer" is an example at the Simpow website but it seems to lack open references.

SINTEF has for their voltage dip studies of IEC type 3 implemented—in both Simpow and PSS/E—a user-built third-order generator model and a two-mass representation of the turbine and generator inertias and a weak shaft there-between. This and a similar study on type 1 were reported in the IEA Wind Annex 21 Final Report 2007(Tande et al 2007).

A comprehensive description of "Stability analysis of an offshore grid supplied by a HVDC-VSC", a recent Simpow-based Norwegian stability analysis (Theisen et al 2011), describes how well documented works on quite other areas (railways) can be revived for new applications like wind power generation and offshore networks.

Today's use of Simpow in the open wind turbine/plant documentation as searched for theses, papers and/or reports via Inspec, IEEE Xplore, Google, etc seems to be limited.

4.2.5 DIgSILENT PowerFactory

DIgSILENT located in Gomarigen/Tübingen develops the integrated power system analysis software PowerFactory.

PowerFactory contains several different simulation modes such as power flow, phasor simulation and instantaneous values and is one of the commonly used simulation packages for modeling large power systems. It has a rather large model library that includes wind power models. Both AC and DC nets can be simulated.

The modeling capabilities of PowerFactory allow the inclusion of complex control dynamics, new generator technologies, blade control and wind turbulence. Some highlights of the current version reads:
• Integrated stability and transient (EMT) simulation
• Integrated modeling of large wind power plants
• Virtual power plant model

PowerFactory is widely used for several wind power applications.

4.2.6 PSCAD/EMTDC

PSCAD stands for Power System Computer Aided Design, EMTDC is the simulation core and stands for ElectroMagnetic Transient including DC. PSCAD/EMTDC is a very widely used simulation package for detailed instantaneous value simulation of different parts of power systems.

PSCAD is owned and developed by Manitoba Hydro International and can simulate very fast transients down to the nano-second range. It is for instance used for isolation coordination studies.

PSCAD/EMTDC is used for modeling both transients in passive power systems and power electronics.

PSCAD allows the user to interactively change the model input during simulation.

PSCAD/EMTDC can be interfaced with Simulink and indirectly with other simulation packages such as ADAMS a simulator for mechanical systems that can model WTGs (Tande et al 2007).

4.2.7 Dymola

The Dymola simulation platform is developed by Dynasim, a company within Dassault Systèmes that is a leading company specializing in 3D and PLM (Product Lifecycle Management) software. Dymola is an open, object-oriented tool for modeling and simulation of integrated and complex systems. Dymola allows integrated and simultaneous modeling and simulation of products coming from multiple engineering disciplines.

The user need not convert the equations to assignment statements. This is done symbolically by Dymola. Algebraic loops are automatically solved. Approximate state event handling suitable for real-time simulation is supported.

Dymola is based on the Modelica open standard language that contains many open model libraries in various domains, see further in 4.6.1. There are many wind power models developed at several universities and recently an Electric Power Library was released from Modelon including wind power models.

Dymola can translate a physical model to an S-function, MATLAB code, or MEX-file which can be used as a block in Simulink. Dymola also supports integration of standard programming languages such as C/C++. Dymola can export models written in Modelica as C- code that can be interfaced with many different power system simulators such as PSS/E and DIgSILENT.

Dymola also support export of models as Functional Mock-up Interface models (FMI models), this is a standard format for package the C-code so it can be used by other simulators. (http://functional-mockup-interface.org/)

4.3 On modeling complex power system components in different simulation tools

The recent development in advanced transmission technologies, such as VSC-HVDC and FACTS opens up new possibilities for improving reliability and utilization of power grids. Detailed models for various dynamic simulation tools such as PSS/E, Power Factory, PSLF, Simpow, Netomac, etc. are needed to enable electric utilities and regional transmission organizations evaluate the operational benefits of incorporating the VSC-HVDC and FACTS devices as feasible planning alternatives using the simulation tools of their choice.

For the development of generic models of WPPs and their use, there is a need for modeling complex power system components in different simulation tools. Development of complex models for advanced power system components using VSC-HVDC is an example (Björklund et al 2008).

A model for power system simulation purposes can cover different aspects from steady-state analysis to dynamic response simulation. Also, a wide range of simulation tools are used by different utilities. The focus of the work is on the dynamic representation of complex power system components in different simulation tools.

The model is divided in to two parts, the tool dependent interface and a common component. The common component contains the control system while the tool dependent interface contains the AC and DC components. The tool dependent interface is implemented as a normal user defined model in the simulation tool while the common component is implemented as precompiled a dynamically linked library, e.g. a DLL-file on windows. In this way the complex control system does not need to be re-implemented in all the simulation tools.

The feasibility of such a tool independent modeling approach has thus been investigated with VSC-HVDC transmission systems as an example. The common component is general and can be interfaced with any simulation tool that permits linking of an external application. The performance of VSC-HVDC model implemented in this novel way was evaluated for PSS/E and Power Factory and found to be satisfactory for power system dynamic stability analysis. The common component based VSC-HVDC model has also been implemented in Netomac.

A number of test cases were used to verify the performance of implemented VSC-HVDC models in PSS/E and Power Factory. The defined test cases include step changes in active power reference, reactive power reference, ac voltage reference, dc voltage reference, three-phase ground fault, etc. For each case, three simulations were performed.

In this verification, the performance of common component based VSC-HVDC models is benchmarked with the results of the existing, tool dependent VSC-HVDC model in PSS/E. The existing, tool dependent VSC-HVDC model in PSS/E has demonstrated good agreement with PSCAD/EMTDC simulation results for different time steps from 0.5ms up to 10ms. The PSCAD/EMTDC model is a replica of the complete VSC-HVDC control system.

4.4 Revival of a Simpow experience in other areas for use in wind power

This comprehensive description of a recent Simpow-based Norwegian stability analysis (Theisen et al 2011) is included here to describe how well documented works on quite other areas can be revived for new applications like wind power generation and offshore networks.

"Stability analysis of an offshore grid supplied by a VSC-HVDC" is a recent academic wind power plant study that uses Simpow (Theisen et al 2011). This NTNU (Norges teknisk-naturvitenskapelige universitet) work establishes a conceptual offshore AC grid with 2 oil platforms, 2 wind power plants and a VSC-HVDC, which connects the grid to DC transmission grid.

The VSC-HVDC is implemented using a predefined model in Simpow.

The model is built for a three phase PWM converter with GTO valves. It was originally designed for static frequency converters in railway applications. The model is intended for analysis of power flow and electromechanical transients, under symmetrical conditions.

It is therefore sufficient to consider only the fundamental frequency of the voltages and currents, on the AC side, and average values on the DC side.

As these values will be independent of the types of valves it can represent a PWM converter with IGBT’s.

The rotating machines are modeled with the standard induction machines in Simpow (Simpow Manual Chap. 2.2.11 and 4.2.13)

Each wind power plant was implemented with four aggregated full converter wind turbines at a rating of 50MW. A predefined model of an FPCWT/FSC/FCWT (Simpow Manual Chap. 17) is used for each turbine. The model regulates the power according to wind speed in order to assure maximum power extraction. A voltage regulator adjusts the reactive power from the wind turbine converter in order to keep the nominally 36 kV bus to unity p.u. value.

The rating of the VSC is 400MVA with a nominal output voltage of 320 kV.

The simulations show that the grid does sustain good power quality as long as the connection to the multi-terminal DC grid is in operation

4.5 Summary

Many simulation tools exist and some have to some extent wind power models. Validated (generic) models fulfilling most requirements do exist as well as turbine generator simulation tools platforms. Regarding turbines type 3 and 4, there are turbine models since the end of 2010 for example those in the WECC Wind Plant Dynamic Modeling Guide Table 1 & 2 and implemented in PSS/E simulation platform.

Scaling of Generic WTG Models for generic simulation of wind power plants is covered in the report’s section 4.3. “By scaling the generator and turbine base capacity to the total generator MVA and total MW rating, respectively, WPPs of any size can be represented.” This can naturally be done with divisions into sub-plants with separate controllers as mentioned in this report's section 2.3 (Figure 2).

Complex power system components like HVDC transmission systems were successfully simulated in different simulation tools.

However, present simulation tools vary much in what type of wind turbine models implemented and the way to implement new models. They also differ in time-scales and performance regarding both accuracy and simulation time.

The models vary much depending on selected base equations and how the base equations are implemented into a simulation language. Equations are normally selected based on balanced criteria between performance and accuracy. The results of the simulations will vary dependent on the numeric solvers in the different simulation tools.

Even when model standardization is in place, the implementation of the models will vary for each simulation tool and the exchange of open models will still be an issue.

4.6 Need for an independent simulation language

Generic model standards can be described in many different ways, the most common way are through a combination of natural language, equations and block diagrams.

In order to reduce the risk of misunderstandings it is good to have executable reference implementations in a standardized executable format.

This language should ideally be a high level language for modeling dynamic systems.

If the language could be used from different simulation tools it could also make it faster to move the models to a new simulation tool.

Many simulation tools can interface with C or C++ code but since it is not a dedicated modeling language the source code tend to be hard to read and dependant on the numeric solver. A dedicated modeling language such as Modelica is easier to read and the causality, the relationship between cause and effect, makes the model more general. A Modelica model can be compiled to C-code if needed, for example by Dymola.

4.6.1 Modelica as an example

Modelica is a non-proprietary, object-oriented, declarative, equation based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents (www.modelica.org).

The free Modelica language is developed by the non-profit Modelica Association. Modelica Libraries with a large set of models are available for download. (Modelica, 2012) Especially, the open source Modelica Standard Library contains about 1280 model components and 910 functions from many domains.

Several simulation tools using Modelica are available commercially and free of charge, such as:

- CATIA Systems
- Dymola
- LMS AMESim
- JModelica.org,
- MapleSim
- MathModelica
- OpenModelica
- SCICOS
- SimulationX
- Vertex.

Modelica models can be imported conveniently into Simulink using export features of Dymola, MapleSim, SimulationX and Vertex.

The Modelica Association is a non-profit organization with members from Europe, U.S.A. and Canada. Since 1996, its simulation experts have been working to develop the open standard Modelica and the open source Modelica Standard Library.

Many universities and companies use Modelica because of the unified approach to physical modeling.

Industry is increasingly using Modelica for model based development. Especially, many automotive companies, such as Audi, BMW, Daimler, Ford, Toyota, VW use Modelica to design energy efficient vehicles and/or improved air conditioning systems. Also power plant providers, such as ABB, EDF, Siemens use Modelica, as well as many other companies.

Research projects within Europe spend 54 Million € in the years 2007-2012 to further improve Modelica and related technology. This is performed within the ITEA2 projects EUROSYSLIB, MODELISAR and OPENPROD.

5 Description of previous and ongoing work

There are many works/documents that include simulation models for wind turbines. This chapter is limited to mainly models for power system studies; there are of course many other types of models for mechanical and aerodynamic studies. Most of these documents focus on how the wind power reacts to short circuits and other disturbances in the external grid. Long term (30 seconds and more) dynamics and the ability to react on external signals are not well studied.

Our focus in V-379 is on Type 3 and 4, and on works written in Scandinavian, English or German, aiming at a North-West European geographical application area where Vindforsk's stakeholders are mainly active. With the selected center of attention, documented North American, IEEE and IEC activities are comprised as well as those of the EU/EC.

Some of the references found include some guidelines on how to aggregate complete WPPs in to one or a few big equivalent wind turbines but it is generally not their focus. The Western Electricity Coordinating Council Wind Generator Modeling Group (WECC WGMG) produced guidelines for modeling wind power in their area. (WECC 2010). This work has laid the foundation for the two ongoing standardization projects, IEC 61400-27-1 and the corresponding project in IEEE Working group on Dynamic Performance of Wind Power Generation.

The PhD thesis "Dynamic Models of Wind Turbines: A Contribution towards the Establishment of Standardized Models of Wind Turbines for Power System Stability Studies" (Perdana 2008) gives a rather complete discussion on modeling of wind turbines and how to aggregate them to model WPPs. The goal is to find models that can be modeled in PSS/E with an integration time step as long as 10 ms.

A number of reviews, surveys and text books are also included.

5.1 WECC Wind Power Plant, Dynamic Modeling Guide and IEEE

5.1.1 Description

This work started at "Western Electricity Coordinating Council: Modeling and Validation Work Group" and was published in the guideline "WECC Wind Power Plant, Dynamic Modeling Guide" (WECC 2010). This work is now the foundation in the ongoing process of model standardization at IEEE and to some extent the process with IEC 61400-27-1. The WECC guidelines also contain recommendations for aggregating wind plants.

The work by WECC is for example described in (Muljadi et al 2010)

All the basic wind turbine types in section 3.3 are modeled.

Some of the models are validated against measurements and vendor specific models in (Asmine et al 2011).

In the published material it seems hard to separate the IEEE project from the WECC WGMG project, they seem to be done in very close cooperation.

GE WTG models were used as the basis to develop the generic Type 3 and Type 4 WTG models. (Ellis et al 2011) WECC has also proposed a standardized benchmark system for testing fault ride through in WTG models.

5.1.2 Objectives

The WECC WTG models are intended to model dynamic stability following large-signal disturbances such as transmission-level faults. The guidelines are mainly intended for the models submitted to WECC for wind power plants in the area they are responsible for. After some time to refine the models they will also be used for interconnection studies. The IEEE does of course address a wider audience.

5.1.3 Models, Timescales and Simulation tools

The WECC WTG models are intended to be used with integration time steps of 1 to 5 milliseconds.

The generator model for wind turbines type 3 does not have any states for the fluxes. The protection models have several set points and delays and are more complex than the IEC model that is described later in this chapter.

The models have been implemented in (GE) PSLF (WECC 2010) (Sanchez-Gasca et al 2009) and Siemens PTI PSS/E. (Lin 2011)

5.1.4 Generic Simulation Model for DFIG and Full Size Converter based Wind Turbines

There are European-based proposals to improvements of existing WECC /IEEE type 3 (DFIG/DFAG) and type 4 (FSC/FCWT/FPCWT) generic models. Reactive power contribution during grid faults and during voltage recovery are proposed, e.g., (Fortmann 2010) and (Fortmann et al 2010). These works take into account technological developments and validation experiences with the European multi-author paper’s companies which include turbine R&D in manufacturing, operation and protection as well as in academia.

The proposed models agree well with measurements of active and reactive fault currents.

5.2 IEC 61400-27 Electrical simulation models – Wind turbines

5.2.1 Description

This is an ongoing project towards an IEC standard of dynamic simulation models for wind power turbines and plants.

5.2.2 IEC 61400-27-1

IEC 61400-27-1 is an ongoing effort to standardize generic simulation models for individual wind turbines for transient stability simulation in large power systems. (IEC 61400-27-1, 2011), (Sørensen et al 2011)

IEC 61400-27-1 tries to make the models as modular as possible.

Four different types of wind turbines are modeled:

1. Fixed speed squirrel cage induction generator
   - 1A Without blade angle control
   - 1B With blade angle control

2 Wound rotor asynchronous generator with controllable rotor resistance and blade angle.

3 DFIG turbines with pitch control

4 Full power converter and pitch control
   - 4A With chopper in the DC-link, neglects mechanical and aerodynamic parts.
   - 4B Without chopper in the DC-link, includes a two mass mechanical model and assumes constant aerodynamic torque.

These definitions are the definitions used in this report.

IEC 61400-27-1 also comprises methods for validating the simulation models.

5.2.3 IEC 61400-27-2

This is a future standard that is planned to extend IEC 61400-27-1 to model large wind farms/plants including plant controller. (IEC 61400-27-1, 2011) (IEC 61400-27-2, 2013) The scope are more described by, (Sørensen 2010), it includes:

> "Scope of IEC 61400-27 – part 2
> Wind turbine modeling must define:
> • Generic dynamic models for topologies / concepts on market
>   • Auxiliary equipment
>   • Wind power plant control

- Methodology to create models for new concepts
- Models refer to wind ower plant point of common coupling
- Independence on simulation tool
  - To outmost degree
  - With clear definition of interface to simulation tool
- Validation”

5.2.4 Objectives

The objective is to get a free and standardized model of individual wind turbines and complete WPPs for dynamic simulations. The models are intended for modeling the response of wind turbines due to disturbances in the power system and do not deal with variations originating in turbulence and other wind variations. The goal is that the standard models should be included in simulation software packages for dynamic power system simulation. Wind turbines operating in weak grids such as island operation are not covered.

5.2.5 Models, Timescales and Simulation tools

All grid frequency signals are modeled with fundamental frequency positive sequence only for use in electromechanical dynamic simulations. The models try to capture dynamic phenomena up to 15 Hz. The models are specified to be able to run with integration time steps of up to 5 ms. The draft explicitly states that the models are not intended for long term stability studies and gives a typical simulated time of 30 s. It assumes constant wind speed during the simulation. The models are defined as a number of sub models defined by block diagrams intended to be implemented in different simulation tools. Some model blocks such as squirrel cage induction generator are not specified, instead it is recommended to use the standard model in the power system simulator.

5.3 Dynamic Models of Wind Turbines, PhD Thesis

5.3.1 Description

Generic dynamic models of wind turbines for stability studies were fairly early proposed in Sweden (Perdana 2008), a PhD-thesis. Response accuracy of the proposed models is validated against detailed models and, in some cases, against field measurement data. Aggregated models of wind power plants are studied. A single equivalent unit representation of a wind plant is found to be sufficient for most short-term voltage stability investigations. The results show that non-linearity’s due to the maximum power tracking characteristics and the saturation of electrical controllers play no important role in characterizing WPP responses. For a medium-term simulation, which may include wind transport phenomena, a cluster representation of a wind power plant provides a more realistic prediction. This thesis work was financed by Nordic Energy Research (NER), together with Svenska Kraftnät and Vattenfall

5.3.2 Objectives

The purpose of this PhD-thesis is to provide wind turbine models and aggregated WPP models for power system models that can be used in standard positive sequence simulations and are computationally efficient.

5.3.3 Models, Timescales and Simulation tools

The proposed models are developed for positive-sequence phasor time-domain dynamic simulations and are implemented in the standard power system simulation tool PSS/E with a 10 ms time step. WTG types 1, 3 and 4 are modeled

5.4 CIGRÉ Technical Brochure 328, Modeling and Dynamic Behavior of Wind Generation…

5.4.1 Description

"CIGRÉ Technical Brochure 328, Modeling and Dynamic Behavior of Wind Generation as it Relates to Power System Control and Dynamic Performance" (CIGRÉ, 2007) is a general overview of modeling of WTGs.

The main focus is on three phase symmetric fundamental frequency simulation. But some advice is given for simulations with instantaneous values. It also has a chapter on modal analysis. It is rather comprehensive with its 216 pages.

It also gives a god overview of wind power technology in general.

5.4.2 Objectives

The objective is to give a general overview of experiences with modeling wind generation from a power system perspective.

5.4.3 Models, Timescales and Simulation tools

The simulation models focuses mainly on system wide disturbances with a bandwidth below 2 Hz but tries to capture local phenomena also up to 10 or 20 Hz. Typical simulation time is a few seconds up to tens of seconds.

It also includes recommendations for static power flow modeling in standard programs and describes the approximations that are needed to make it fit standard power flow programs. Since it is an overview presenting models and results from many different sources it describes the use of a wide selection of simulation tools.

5.5 NREL 5 MW Reference Wind Turbine for Offshore System Development

5.5.1 Description

This is a reference model of a 5 MW wind turbine (Jonkman et al 2009); it was developed by the National Renewable Energy Laboratory in the US.

The model is based on public data for wind turbine design with a heavy emphasis on the REpower 5M machine.

This model has very detailed mechanical and aerodynamic models with aerodynamic blade profiles at different radius and stiffness parameters along the blades and the tower. A control system for pitch and generator torque is included but no electric model is included.

This model is widely used in aerodynamic and mechanical studies and it has also been used to model wake effects in wind farms.

5.5.2 Objectives

Provide a common well documented wind turbine for non electrical simulation studies.

5.5.3 Models, Timescales and Simulation tools

No electric models, detailed models of aerodynamic and mechanical system.

5.6 SimWindFarm Toolbox

5.6.1 Description

SimWindFarm is a Matlab/Simulink toolbox for simplified aerodynamic and mechanical wind farm modeling. (Grunnet et al 2010) It was developed in the EU-FP7 project AEOLUS. Given wind farm geometry, wind direction, average wind speed and a wind turbine model it can generate a simulation model that includes wake effects and stochastic wind variations. It includes no electrical models.

5.6.2 Objectives

The objective is to provide a simple simulation tool for simulation of wind farms including stochastic wind field and wake effects. This is useful for example in the development of WPP-controllers for active power control.

5.6.3 Models, Timescales and Simulation tools

The wind field is modeled with a frozen turbulence model and includes wake effects. The average wind speed and direction are considered constant.

The NREL 5 MW Reference Wind Turbine (Jonkman et al 2009), is used as an example. The model includes calculation of fatigue loads with the rainflow count method. The model includes the wind turbine control system but no electrical model. A simple proportional plant controller is included as an example.

5.7 NERC special report: Standard Models for Variable Generation

5.7.1 Description

The North American Electric Reliability Corporation (NERC) special report "Standard Models for Variable Generation" (NERC, 2010) summarizes the status, experiences and need for models for Variable Generation in their area on an overview level, mainly wind power. The main reference for specific wind power models are the WECC wind power modeling guidelines, (WECC 2010). It stresses the need of "valid, generic, non-confidential, and public standard power flow and stability (positive-sequence) models" very much. It states that this is a "present and imminent requirement". The need for aggregated models of complete WPPs is also mentioned.

It is reported that there has been problems to get timely access to proprietary models from the manufacturers. The models have also had problems with convergence and numerical stability.

Numerical interactions between wind turbine models from different manufacturers have been found to be especially problematic since non-disclosure agreements make it impossible to share the information among the manufacturers.

5.7.2 Objectives

The objective is to describe current practice and the need for model standards to describe variable generation. The main focus is on wind power generation.

5.7.3 Models, Timescales and Simulation tools

The positive-sequence models should be valid for 0.1 Hz to 3 Hz and the control system in the models should have validity up to 10 to 15 Hz.

The need for models for extended term analysis including wind speed variations is also mentioned.

In addition to this the report gives an overview on the need for "Detailed Three-phase Equipment Level Models", which is called electromagnetic circuit simulation in this report. These models are necessary for modeling, for example, subsynchronous resonance and subsynchronous torsional interaction. It is stated that:

"This brief section illustrates the need for the availability of detailed 3-phase equipment level models, which cannot be generic. These models are likely to be proprietary and may need to be used under non-disclosure agreements between the vendor and the plant developer/utility."

Since it is an overview presenting models and results from many different sources it describes the use of a wide selection of simulation tools.

5.8 V-311 The Dynamic Impact of Large Wind Farms on Power System Stability

5.8.1 Description

This Vindforsk project was performed as a PhD project by Katherine Elkington at KTH and resulted in the PhD thesis "The Dynamic Impact of Large Wind Farms on Power System Stability". The project deals with wind plants based on DFIG-generators. (Doubly feed induction generators) A reduced simulation model of a DFIG wind turbine is presented and different controllers for damping of power oscillations are developed. (Elkington 2012)

5.8.2 Objectives

The objectives are to investigate the influence of large wind plants with DFIGs on power system stability and to develop controllers for increasing the stability.

5.8.3 Models, Timescales and Simulation tools

The work began with modeling in Matlab but continued with implementation and simulations in Simpow. All simulations assume fundamental frequency positive sequence only. The mechanical system is modeled as a one mass model. The aerodynamics is modeled with a static model. Controllers for power and pitch angle are included.

5.9 V-358 Implementation of frequency control in wind power

5.9.1 Description

This is a Vindforsk project regarding frequency control in wind turbines; it is performed by ÅF Industry AB. The project period is April 2011 to June 2012. The study has used a small system in island operation as example. The example has 240 MW Hydro power and between 9 MW and 120 MW wind power. The wind variation introduces rather large frequency variations in the system. The regulator gives some improvement even without reducing the power set point and gives even larger improvement if operating in delta control mode. (Mehmedovic 2012)

5.9.2 Objectives

The objectives are to design a frequency controller for wind turbines and to evaluate its performance with regards to reduction in frequency variation and efficiency of the wind turbine.

5.9.3 Models, Timescales and Simulation tools

The project was performed using SIMPOW. The frequency controller has been added to the existing wind power plant models in SIMPOW. The used wind model seems to be a static model. Presented frequency variations are in the range of 5 to 50 mHz and simulated time series are about 300 seconds long.

5.10 V-369 PoStaWind

5.10.1 Description

V-369 PoSta Wind is a Vindforsk program conducted by STRI AB during the period July 2011 to October 2012. It contains three sub projects:

I. Study how voltage controllers in wind plants change the damping of inter area electro mechanical oscillations.

II. Study the use of synthetic inertia.

III. Study transient reactive support from wind power

The project focuses on large scale integration of DFIG-based wind power. (STRI 2011)

5.10.2 Objectives

The objective is to give recommendations for new grid codes and guidelines for tuning of control parameters in connection with the three sub projects.

Another objective is also to show how system planers can use PSS/E too simulate these problems. An objective is to find systematic correlations between system characteristics and the results in the simulations.

5.10.3 Models, Timescales and Simulation tools

The project uses electromechanical simulations in PSS/E. The wind power model are assumed to be DFIG.

5.11 DFIG turbine representation for small signal voltage control studies

5.11.1 Description

This paper (Martínez et al 2010) compares a simulation of a type 3 (DFIG) WPP in PSCAD/EMTDC with a simple transfer function model.

The WPP has a central voltage controller (Plant Controller) and the model includes communication delays and losses in the collection grid.

The transfer function model showed good agreement with the detailed model as long as the converter did not saturate and the short circuit ratio was high enough to not introduce significant coupling between active and reactive power.

5.11.2 Objectives

The objective is to develop and validate a linearized transfer function model of a type 3 WPP.

5.11.3 Models, Timescales and Simulation tools

The described linearized transfer function model is a fundamental frequency positive sequence model. The model is described as a transfer function based on the Laplace transform.

A detailed model in PSCAD/EMTDC is used as a reference model.

5.12 Need for Standardization of Wind Power Models for Stability Studies

5.12.1 Description

In the paper “Need for Standardization of Wind Power Models for Stability Studies” (Persson et al 2009) Vattenfall highlights the need for standardization of WPP models. Different models representing different but similar DFIGs are compared with regards to allowable short-circuit ratio, big differences are found that could be due differences in the actual machines or in the accuracy of the models. It points out: “Often, in agreements between buyers of wind power turbines and developers of wind power turbines, the developers of the models avoid to take responsibility of the behaviour and the accuracy of the models.”

5.12.2 Objectives

The objective is to show that different models of the same WTG concept can give rather different results and that without open models it is hard to interpret the results.

5.12.3 Models, Timescales and Simulation tools

Four different WTG models are used, three of these are implemented in PSS/E and one is implemented in Simpow.

5.13 Results of survey of Requirements for Generator Data And the Need for confidality

The result of the survey that was mainly sent to TSOs of different countries is reported in the paper: "Results of survey of Requirements for Generator Data And the Need for confidality", (Southwell et al 2006). The survey was sent to 34 members of CIGRE Study Committee C1, and 17 answered. The following questions were used in the survey:

- Is it a requirement that a generator model must be provided before a generator can be connected to a network?
- Is it a condition of connection that the generator data will not be kept confidential?
- What is the lowest voltage or generator size that the rules apply to?

The answers ranged from Argentina where non-confidential and non-black box models are required for all WPPs above 10 MW and Croatia were no generator models at all are required before connecting a generator.

The survey found that there was a great interest in dynamic models and that there are a "lack of confidence in models supplied in the form of a 'black box'".

5.14 Other contributions

Essential contributions on type 1 and type 2 turbines (Akhmatov 2010) seem difficult to download but are referenced as input for overview (Sørensen et al 2011) while many of Akhmatov's contributions seems more comprised in the committee-based works, e.g., in (CIGRÉ 2007). During the V-379 work, we have not found a similar multi-professional, academic-manufacturer-TSO-WG, single-author paper on type 3 and type 4 to use as reference in our chosen focus for future works on generic models of WPPs. Yet, there are two such slide sets on EPRI's and Vestas views on type 3 and type 4 generic wind turbine models (Pourbeik 2011) (Badrzadeh 2011). Two essential conclusions from the latter slide set reads: The level of details provided to the user must be consistent with the capability and bandwidth of simulation tools adopted for bulk transmission system studies. Furthermore, there is a need to distinguish between transient stability models used for model certification and those used for bulk transmission system studies.

The WECC WTG models were recently included in the PSS/E simulation package (Lin 2011).

Experiences from upgrading of a couple of company-owned simulation packages in the USA form a subject for a comprehensive discussion memo in the public domain on structure and functionality of wind generic models (Kazachkov et al 2011) as part of standing committee works in the WECC's Variable Generation Subcommittee (VGS) regarding electric system reliability and market issues of mutual applicability coordinated by the Joint Guidance Committee (JGS). Similar proceedings are on their way in Europe, e.g., in the

NORDEL, the ENTSO-E[1] (https://www.entsoe.eu/rd/), etc what regards Vindforsk's vicinity.

Dynamic models for WPPs were the main issue for the IEA Wind Annex 21 work (Tande et al 2007). Model developments were then ongoing among the annex's nine nationality participants in the task using various software tools: Matlab/Simulink, PSS/E, Simpow, DigSILENT and ADAMS with PSCAD/EMTDC.

The paper "Dynamic fault simulation of wind turbines using commercial simulation tools" (Lund et al 2005) compares the standard library models of a 2 MW type 1 wind turbine in different commercial simulation tools. The response to short circuits in the grid was simulated. Both symmetric and unsymmetrical RMS simulations and full electromagnetic transient simulations are presented. The tested simulators are PSCAD/EMTDC, Powerfactory, SIMPOW and PSS/E. Generally the agreement between the simulators is found to be good.

The book: "Wind power in power systems" (Ackermann, editor, 2005) gives a very wide picture of wind power. Especially chapter 27 "Full-scale Verification of Dynamic Wind Turbine Models" by Vladislav Akhmatov was found highly relevant. It highlights the importance of dynamic inflow.

A summary of the most important characteristics of wind turbine generators applied in modern wind power plants is presented by IEEE PES Wind Plant Collector System Design Working Group (Camm et al, 2009). Various wind turbine generator designs, based on classification by machine type and speed control capabilities, are discussed along with their operational characteristics, voltage, reactive power, or power factor control capabilities, voltage ride-through characteristics, behavior during short circuits, and reactive power capabilities. Turbines from IEC Type 1 to 4 are covered. A hardly any power electronic based "Type 5" turbine system is also included in the referenced IEEE wind plant work. The fifth type consists of a typical WTG variable-speed geared drive train connected to a mechanical torque-speed converter coupled with a synchronous generator to the collection network.

In depth description of relevant converter technology is given in the book "Grid Converters for Photovoltaic and Wind Power Systems" (Teodorescu et al 2011)

SCADA and wind power plant controls have during many years constituted an essential area on the way to today's large scale wind generation. IEEE PES Wind Plant Collector System Design Working Group discusses in (Badrzadeh et al 2011) the range of application for SCADA and control systems in a wind power plant, the most important SCADA and control system considerations, and contractual requirements for SCADA and control systems. The paper is a well reviewed result of two years of concerted effort by the authors and the working group well worth to comprise when planning Vindforsk's coming wind R&D program despite its lack of the words *"generic model"*.

5.15 Summary

There is a lot of ongoing standardization but no final standard for the modeling of wind turbines for transient stability studies. There are also some recommendations for aggregation of the wind turbines in a WPP to one or a few up scaled wind turbine models. Few models include dynamic inflow which can be important in controllability studies. Generic models for simulation of active power control including wake-effects and stochastic wind variations such as SimWindFarm exist but has no electrical model connected to them. No generic models suitable for modeling controllability of WPPs that include both electric and aerodynamic models were found. Such models would be needed to model plant controllers and the ability to provide different combinations of ancillary services.

A summary of some key facts on some of the projects presented in this chapter can be seen in the table below:

	Tools	**Model types**	**Turbine Types according to section 3.3**
WECC… Modeling Guide	Implemented in (GE) PSLF and PSS/E	SYM-RMS	1, 2, 3, 4
IEC 61400-27-1	Unknown, not released yet.	SYM-RMS	1, 2, 3, 4
PhD Thesis Perdana	PSS/E and Matlab/Simulink	SYM-RMS	1, 2, 3, 4
CIGRÉ Technical Brochure 328	PSS/E and PowerFactory	SYM-RMS, Power Flow, EMT	1, 2, 3, 4
NREL 5 MW Reference WT	Arodynamic and mechanical tools e.g. FAST, ADAMS etc.	Aerodynamic, mechanical	3, 4
SimWindFarm	Matlab/Simulink	Stochastic wind, Wake, aerodynamic, mechanical.	3, 4
V-311 PhD Thesis Elkington	Matlab and Simpow	SYM-RMS	3
V-358 Frequency control	SIMPOW	SYM-RMS	4
V-369 PoStaWind	PSS/E	SYM-RMS	3

SYM-RMS = Electro mechanical three phase symmetric fundamental frequency simulation.

6 User survey

A survey has been made with some of the potential users. The questionnaire in appendix A was used. The answers are summarized below. The answers are not necessarily consensus of the whole organization.

The questionnaire was sent to Swedish National Grid (Svenska Kraftnät), ABB, EON and Vattenfall. Within EON the questionnaire was answered by ECR, (E.ON Climate & Renewables)

Not surprisingly due to their varied activity ABB Corporate Research indicated that they performed a wide range of simulations in different tools while the others had more limited range of simulations and tools.

6.1 Response from potential users

6.1.1 What is your current practice regarding modeling of wind power plants?

All respondents indicated that wind power plants of type 3 and 4 (DFIGs and Fully rated converter) was the most important to model. EON indicated that fully rated converter wind turbines will be the most important in the future.

ABB do many types of simulations.

Otherwise the models seem to be used manly for fundamental frequency positive sequence simulations and some short circuit analysis.

Generally it seems that if site specific models are available they are used in all simulations but sometimes generic models are used for general power system simulations

Swedish National grid use the GE model for DFIG:s and the Enercon ExF1 model for full converter turbines for PSS/E simulations while they model wind power in ARISTO as controllable load.

6.1.2 What is your current practice regarding the usage of simulation tools?

All the respondents uses PSS/E, Swedish National grid uses the internally developed ARISTO and ABB uses PSS/E, PowerFactory, PSCAD/EMTDC and Matlab/Simulink.

Swedich National grid uses models included in PSS/E or downloadble from the PSS/E support page.

Eon and Vattenfall uses models supplied from the wind turbine manufacturer.

All the respondents indicated that they to a certain degree needed to assume that the used models were correct. Eon answered that they probably will build expertise to verify the models.

Eon plans to use DigSilent to cross check the PSS/E results.

Swedish National grid and Vattenfall indicate that they will in most cases not be able to translate the models to other simulation tools/future versions of the simulation tool.

Swedish National grid and Eon answer that manufacturers are probably not responsible for providing updated models during the life of the WPP. Vattenfall says the manufacturers are responsible for providing updated models during the life of the WPP. And according to ABB it is treated on a case by case basis.

6.1.3 What is your view on the possibilities on WPP control models?

The respondents saw a need for the models to be upgradable and retunable, at least if the WPPs can de upgraded but also for testing purposes.
A separate plant controller is needed in at least some cases but according to Swedish national grid it does not necessarily need to be modeled separately in aggregated WPP-models.
According to Vattenfall, if the controllers in the WPP is upgraded the manufacturer should upgrade the models too.
According to Swedish National Grid it may be necessary for WPP controllers to be updated depending on the development of grid codes in the next 20 years.
According to ABB it should be possible to upgrade the controllers in WPPs to provide more ancillary services during the life of a WPP. According to Vattenfall the WPP models should include future possible features that one wants to study; alternatively the user should have the possibility to add sub models to try/test new features.
According to Swedish National grid, Vattenfall and ABB all the control modes mentioned in the questionnaire will be used in the future, they were: voltage control, frequency control, active power set point, reactive power set point, delta control. According to Eon mainly active power set point and reactive power set point will be used, they are already today controlled by the DSO/TSO at some wind farms.

6.1.4 What is your view on the usefulness of black box confidential models, white box confidential models, open models and standardized models?

According to Swedish National Grid it is more difficult to understand unexpected results from black box models. Vattenfall points out that the source code is not necessary in order to understand the simulation results but that a good explanation on how the model works and how it must be implemented is useful.
ABB needs to exchange information in a way that is prevented by the use of confidential WPP models while it has not been an issue for Swedish National grid so far.
The respondents think the administration of many different manufacturer specific models will be a problem.
Swedish National grid states:
"It would be useful to have a model standard, so that all models could be treated in the same way. SvK would like them to be able to be used in PSS/E.

All state variables should initialize to zero, and have recommended default values.”
Vattenfall states:
“This depend on how the model provider makes the models, for example, up to no now one manufacturer has used the same model name for different version meaning if I want to use a new one for an additional turbine/park I must update the existing ones also, very time consuming and a source of error.”
The respondents would like to have a model standard but Vattenfall point on some difficulties:
“It would be good but there are difficulties, FPC gives you basically endless possibilities, a standard model can never cover all possible manufacturer solutions. To use a standard model or not depends also on the kind of study youre doing.”
Swedish National grid points out that they are involved in both internal and external studies which aim at developing suitable generic models for wind turbines. Vattenfall think it would be useful if the models would be specified in some standard format, perhaps CIM.
Swedish National grid states:
“For general studies clear descriptions of the models should be available.
For connection studies it may be necessary to have more detailed descriptions of the models. “
ABB thinks it is important that standardised models have an open reference implementation.

6.1.5 Which essential areas for establishing [generic] WPP models have we overlooked with our questions?

None of the respondents had anything to add.

6.2 Summary

An overview of the type of simulations, simulation tools and models used can be seen in the table below.

Organisation	Type of simulations	Simulation Tools	Models
Swedich National grid	Three phase symmetric fundamental frequency	PSS/E ARISTO	Included in PSS/E Controllable loads in ARISTO
Vattenfall	Three phase symmetric fundamental frequency, EMT for lightning and short circuit simulations.	PSS/E Power Factory PSCAD	From the manufacturer
EON	Short circuit analysis and LVRT simulations	PSS/E, PowerFactory	WTG-PSSE-module from the manufacturer
ABB	Many different depending on purpose.	PSS/E, PowerFactory, PSCAD/EMTDC and Matlab/Simulink	Different sources

Eon answered that they have performed low voltage ride through simulations, I assume that they are done as three phase symmetric fundamental frequency.

The most used simulation types and analysis seems to be three phase symmetric fundamental frequency and short circuit analysis.

The practice seems to differ regarding who is responsible for upgrading the simulation models if needed.

Swedish National grid sees a need to be able to upgrade the controllers in the WPPs if the grid code is updated. This will make it necessary to update the simulation models to.

Most respondents think many different control modes will be used on WPPs in the future.

Different types of standards for wind power models are needed. Vattenfall points out that even such a simple standard as consistent naming of wind turbine models can be very useful.

7 Conclusions

Many wind turbine models exist today at different companies, developers, suppliers, universities etc and the models vary in accuracy and time-scales dependent on applications.

The expansion in onshore/offshore wind power will involve expansion of new technologies such as power electronics (VSC-HVDC) and automation. New technology leads to new system configurations and new functions and also the need of additional dynamic models.

A questionnaire was sent to Swedish national grid (Svenska Kraftnät), ABB, EON and Vattenfall. The answers indicated a need for standardized models, and pointed out some difficulties. The general conclusion was that models for WPPs based on wind turbines of type 3 and type 4 (doubly feed induction machine and full power converter) will be the most important models.

The ambition is to have a common open model platform enabling easy model exchange between industry and universities.

The WECC work seems to lay a foundation for an upcoming de facto standard in wind turbine modeling. Formal standards are being developed by both IEEE and IEC. Early works within Cigré and IEA projects prepared the grounds. These models are intended for simulation of grid disturbances in large grids.

The models are not intended for long term studies or studies including the usage of a plant controller with external control signals and wind variations. It is unclear what extensions if any would be necessary to make the model valid for long term studies.

Dynamic inflow, the lag in local wind speed after changes in pitch angle and turbine speeds are often neglected in power system stability studies but it is probably important in the modeling of the controllability of active power in timescales between one second and one minute. For longer timescales wake effects, i.e. how the local wind speed depend on the power previously extracted by other turbines, needs to be modeled.

Almost all proposed generic wind power models for power system studies are for three phase symmetric fundamental frequency simulations.

The modeling of complete WPPs lack standardizations today. Some ways to aggregate a wind power plant in to one or a few machines are suggested.

The modeling of the plant controller seems not to be included in the coming model standardization.

There is a need for independence on simulation tool where an independent common simulation language is essential.

8 Future work

8.1 General

R&D projects for WPPs are needed as **future works**. Control, simulation and grid integration are adjoining areas.

• Headlines comprise:

1. Ancillary services
2. Voltage control strategies;
3. VAr and/or active power reserve concepts;
4. Active current control during grid faults;

• WECC has considerable simulation experiences of generic models and validation experiences.

• Complex power system components like HVDC transmission systems were successfully simulated in different simulation tools by ABB and other actors.

• Robust PLL-based control of power electronic (PE) converters in wind power generators and transmission and distribution are essential devices that are under strong development.

• There is a continuous integration of software and hardware in (non-) safety-/security-critical parts. Complex models of advanced power system components will facilitate several simplifications.

It is proposed to carry out a follow-up a combination of these dotted aspects.

There will remain a number of black box confidential models, white box confidential models, open models and standardized models. Future works will reorganize and maybe clean up among these. As power electronic (PE) converters are ubiquitous in megawatt scale wind turbines, there will appear several ways to upgrade the WPP control circuitry during the WPP life-time, both software and hardware. PE technology remains in a continuous development phase in contrast to mature thermal plant synchronous generator (SG) non-PE main circuit systems. The WPP PE circuits will perhaps be exchanged after 10 to 12 years operation with better WPP energy yield or total system performance as result.

There are always exchanges and upgrading of electro-mechanical switches due to wear and to taking into account technological developments and validation experiences. Generic models will be used in combinations with dimensioning and assuring circuit functions and assessing the risk in the form of a failure mode and effects analysis (FMEA). On the other hand, protection devices and their actions for fail-safe operation ought to be simulated with detailed models what regards internal aspects.

It is important to consider the power quality issues of auxiliaries' supply voltage. Auxiliaries in wind turbines and WPPs do have low-voltage-ride-through issues, sensitivities to asymmetries, step change in voltage phase, frequency deviation/ramp in voltage. I some cases these issues need to be modeled.

Sub-synchronous resonance (SSR) disturbances (V-309) might be a risk for failures. SSR has disturbed control signals inside PE-based converters in a thermal power plant.

These and other auxiliary aspects are not included in the references. Yet "auxiliary" is mentioned in the IEC draft and (Badrzadeh et al 2011), but not to the same level of detail as above.

The plant controller tries to minimize wear and tear on the equipment while supplying the requested active power and other services. In the future, the wind plant controller should comprise control of the auxiliaries as well as of the drive-train mechanics for best plant reliability.

8.2 Simulation tools

The electrical parts of the wind turbines as well as the grid are modeled in PSS/E, Power Factory, (GE) PSLF, Simpow, Netomac, PSCAD/EMTDC, etc. The mechanical parts are modeled in similar multi-body dynamics packages for modeling the wind turbine dynamics. Matlab/Simulink is sometimes used to combine the simulations.

Toolboxes like SimWindFarm will appear or be further developed to provide a fast WPP simulation environment for development of WPP control algorithms.

For the development of generic models of WPPs in power transmission and distribution systems and their portable use, there is a need for modeled complex power system components to be used in several simulation tools. Development of portable complex models of advanced power system components using HVDC-VSC is a successful example verified in PSS/E and Power Factory and also used in Netomac (Björklund et al 2008).

Similar complex models for FACTS devices as well as for multi-body dynamics code for modeling the wind turbine dynamics are needed and expected.

8.3 Common modeling language

Even when model standardization will take place, the implementation of the models will vary for each simulation tool and the exchange of open models will still be an issue. It is equally important having a standard specification on how to implement standard models. The best solution would be a standard model language such as Modelica that is independent of simulation tools. Already today 10 different simulation tools use Modelica and the usage is increasing rapidly.

Another issue regarding achieving the same simulation results is the implementation of different numeric solvers in simulation tools. Here might also be a need for a standard in how to implement the various solvers.

8.4 Improved control strategies

As the whole reported work in our V-379, there are efforts to be done to develop open generic models of particular types of generators such as wind turbines to be combined as generic WPP models to cover both the basic operation as well as the ancillary services in the power system. Furthermore, there are always noise components which energize resonances.

Another area (Thorburn 2012) is to control the WPP internally with special regards to trim down internal oscillations and reduce mechanical stress, especially in geared wind turbines in a way similar to the PSS controller technology with regards to reduce oscillations in the power grids operated by TSOs and/or DSOs. Phasor Measurement Units (PMU) or the like will through future works on similar signal analysis be extended to cover turbine-internal torsion and bending aspects in the shaft system. Development of portable complex models of the detailed turbine-drive will hereby be very useful. The benefit of trimmed-down mechanical oscillations will be to extend the life-time of the equipment and to reduce the operational and maintenance costs with the same total energy output due to less down-time and negligibly de-rated operation.

Neither power electronic components nor computer-based signal analysis in automatic control will limit the development of WPP control software and hardware. Cross-bordering R&D will be beneficial for the progress of the area.

8.5 The plant controller

Ongoing work on different model standardizations seems to lack the plant controller and also some parts of the wind turbine control. These control levels play an important role by supplying several functions such as ancillary services.

Future transformation of the power systems will include a large part of controllable units and the coordination of these will be essential in order to keep supply security. New requirements will likely be applied enabling direct control of wind power plants in case of emergency situations.

The plant controller will also have several internal functions to optimize the balance between generation and maintenance costs.

The plant controller and wind turbine controller should be specified and included as a part in the wind power plant model standardization.

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10 Appendix A

Vindforskprojekt V-379: Frågeformulär

2012-06-04

Bakgrund

Vindforsks förstudie V-379 innefattar vad som görs och har gjorts inom området simuleringsmodeller för ”styrning av vindkraftanläggningar”, nationellt och globalt. Speciellt avses modeller för styrning av vindkraftverk och överordnad styrning av hela vindkraftanläggningen samt gränssnitt mellan vindkraftverken, överordnad styrning och systemansvarig (TSO). Syftet med modellerna är att kunna testa och verifiera styrbarheten (ancillary services) av vindkraftanläggningen samt interaktionen mellan anläggningen och kraftsystemet utifrån de krav som ställs från systemansvariga. Fokus i V-379 är standardiseringsarbetet IEC 61400-27 samt Vindforsks projekt V-311, V-358 och V-369.

Ett övergripande mål med förstudien är att formulera vidare forskning inom området (generiska) modeller baserat på en jämförelse mellan identifierat behov och pågående arbeten. Bland de specifika målen är det att:

- Redovisa behovet av modeller utifrån en undersökning av några av Vindforsks intressenter, såsom Svenska Kraftnät, ABB, EON, Vattenfall.
- Sammanställa vilka simuleringsverktyg som används samt de krav som ställs på befintliga/kommande verktyg vid behov och med hänsyn till leverantörsoberoende, öppenhet och funktionalitet.

Frågor och instruktioner

Vi formulerar framför allt öppna frågor. Rapporten skall vara på engelska och vi önskar era svar och kommentarer på det språket. Dessa frågor skickas till Svenska Kraftnät, ABB, Eon, Vattenfall och Fortum, svara på de frågor som berör er verksamhet.

Questions

There is work to be done to develop open generic models of particular types of generators such as wind turbines to be combined as generic wind power plant (WPP) models to cover both the basic operation as well as the ancillary services in the power system. WPPs are often modeled by scaling up a wind turbine model to the desired power with a limited comprising of the real wind plant controller as depicted in Figure 1. In order to describe the needs for such models and the requirements on them we would like you to answer these questions.

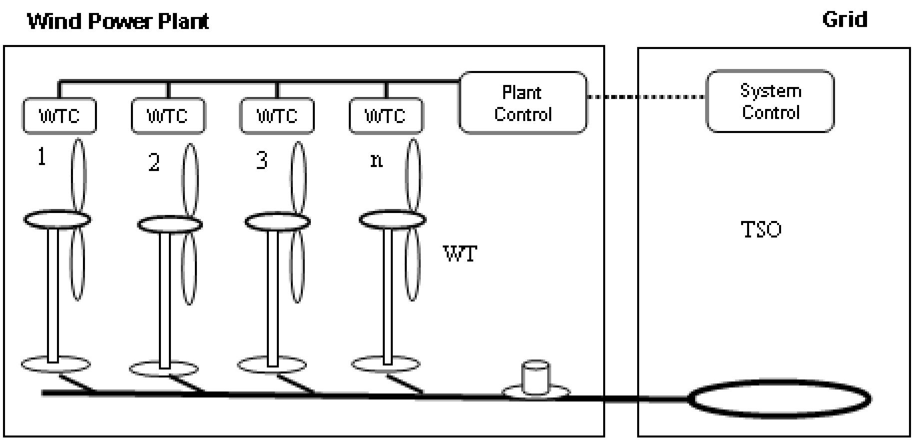

Figure 1 Wind power plant with wind turbine controllers (WTC) and plant control.

The following five questions are designed to be open, the sub questions are provided as hints about the type of information we want in your answers.

1. What is your current practice regarding modeling of wind power plants?

a) What types of WPP models do you provide/require/use?
b) What types of wind turbines do you model? (Fixed speed, DFIG and/or Fully Rated Converter etc.)
c) Which are most important?
d) What timescales do the models cover? (short circuit analysis, instantaneous values or fundamental frequency symmetric?)
e) How are their mechanical systems, aerodynamic transients and control systems modeled?
f) How do you model the aggregation of several wind turbines in a WPP and the effect of the plant controller? (Figure 1)
g) Do you sometimes model WPPs as equivalent synchronous machines?
h) Do you use the same WPP models for both general power system simulations and WPP connection studies?

2. What is your current practice regarding the usage of simulation tools?

a) What simulation tools do you use?
b) Are the WPP models included in a simulation package or provided directly from the WPP manufacturer or developed by you?
c) How do you verify the models and/or the simulation results? (Trust the manufacturer, physical test, analyze of fault recordings or other methods)

d) Will you be able to translate the WPP models to other simulation tools/future versions of the simulation tool?
e) Are the manufacturers and/or owners responsible for providing updated models during the life of the WPP?

3. What is your view on the possibilities on WPP control models?
a) Should the WPP models be able to be retuned and upgraded?
b) Should there be a separate plant controller coordinating the wind turbine controllers? (Figure1)
c) If the controllers (wind turbine controllers and plant controller) need to be updated, how should the models kept up to date?
d) Should updates be able to be performed by persons other than the WPP manufacturer?
e) Should the WPP controllers be updated in order to provide more ancillary services during the life of the WPP?
f) What external control signals and control modes do you think will be used in the future? (voltage control, frequency control, active power set point, reactive power set point, delta control, etc.)

4. What is your view on the usefulness of black box confidential models, white box confidential models, open models and standardized models?
a) How do black box models affect verifying and understanding results?
b) Do you have needs to exchange information in a way that are prevented by the use of confidential WPP models?
c) Will the administration of many different manufacturer specific models become a problem?
d) Are you in need of model standards?
e) What should they cover regarding controllability and the plant controller? (types of specification on equations/functions, implementation in simulation tools, common simulation language to be used in several simulation tools etc.)
f) How do you follow and discuss the development of generic models of wind turbines and their plant controllers?
g) How should they be specified, is open reference implementations important?

5. Which essential areas for establishing [generic] WPP models have we overlooked with our questions?

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