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Wind turbine models - Model development and verification measurements

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Summary

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

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

Based on this report, the PSS/E generic models and some PSCAD/EMTDC models were tested, assessed and analysed.

Availability of wind turbine measurement data for model validation purposes was investigated, and there is data available e.g. of fixed speed wind turbine, DIFG and full power converter equipped wind turbines.

The ancillary services relative to wind power production units are also reviewed in this report.

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1 Introduction

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

There are several different simulation software products available for electrical system and power production simulations. Some of these simulation tools have similar qualities and are developed and delivered by different companies, but on the other hand, different software may have separate modelling and simulation precision, and they serve (best) different purposes. Therefore, the most common simulation tools for electrical systems and components are first introduced in chapter 2. The general background of wind turbine modelling is glanced in chapter 3. In the following chapters 4-6 existing wind turbine and wind farm models for some relevant simulation software are reviewed. Chapter 7 deals with wind turbine model validation data and in chapter 8 PSS/E generic models are tested, assessed and analysed. Ancillary services of power park modules are briefly reviewed in chapter 9 in order to list the requirements and possibilities which may affect wind farm design and modelling.

2 Simulation software review

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

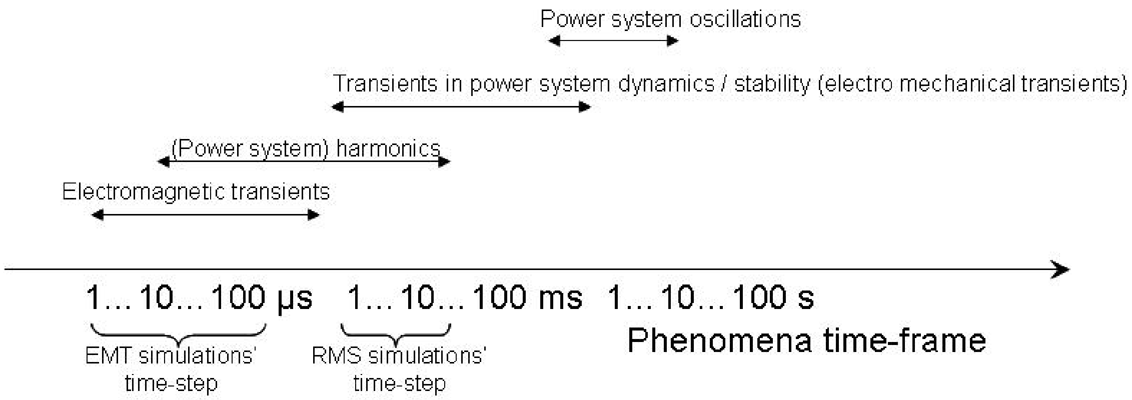


Figure 1. Time-frame of different phenomena to be considered in modelling precision and simulation set up of electrical phenomena.

Some of the commonly used simulation software products are:

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

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

3 Wind turbine modelling background

There is work going on around standard IEC 61400-27 for ”Electrical simulation models for wind power generation”, which will define the generic simulation models for wind turbines and wind power plants [2]. The standard deals with the dynamic models to be used for power system stability simulations. It specifies the level of modelling detail, and which features the different wind turbine type generic models will need to have. The standard presupposes model validation to be based on measurements described in IEC 61400-21. The standard categorizes the wind turbine technologies in four Types. This categorization is also used in context of PSS/E models (see chapter 4).

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

4 PSS/E

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

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

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

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

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

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

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

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

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

PSS®E Wind Package Information

Latest Revision October 13 , 2011

Click to view change log.

Modifications:

Click here to download Protection User Guide.

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

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

Table 3. Generic PSS/E component models for each wind turbine technology type (for PSS/E version 33.1).

<table>
<tr><th colspan="2" rowspan="2">Wind turbine technology type</th><th colspan="5">Component model</th></tr>
<tr><th>Generator</th><th>Electrical</th><th>Pitch</th><th>Aerodyn.</th><th>Mechanical</th></tr>
<tr><td>Type 1</td><td>squirrel cage</td><td>WT1G1</td><td></td><td></td><td rowspan="2">WT12A1</td><td rowspan="2">WT12T1</td></tr>
<tr><td>Type 2</td><td>variable rotor resistance</td><td>WT2G1</td><td>WT2E1</td><td></td></tr>
<tr><td rowspan="2">Type 3</td><td rowspan="2">DFIG</td><td>WT3G1 [1)]</td><td rowspan="2">WT3E1</td><td rowspan="2">WT3P1</td><td rowspan="2"></td><td rowspan="2">WT3T1</td></tr>
<tr><td>WT3G2</td></tr>
<tr><td rowspan="2">Type 4</td><td rowspan="2">full power converter</td><td>WT4G1 [2)]</td><td>WT4E1 [2)]</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>WT4G2 [2)]</td><td>WT4E2 [2)]</td></tr>
</table>

1) the component model is retained for back-ward compatibility, WT3G2 is recommended instead to be used for new simulation setups

2) WT4G1 and WT4E1, as well as WT4G2 and WT4E2 ought to be used only together, i.e. G1 and E2, or G2 and E1 models cannot be used together

5 DIgSILENT PowerFactory

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

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

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

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

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

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

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

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

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

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

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

6 PSCAD/EMTDC models

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

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

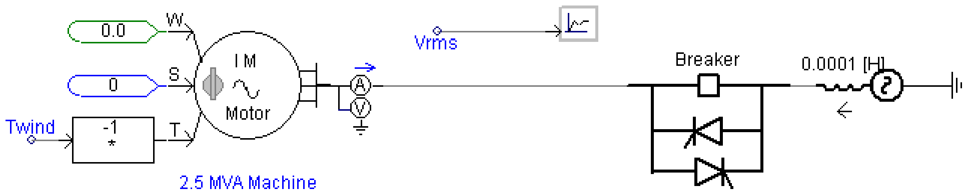


Figure 2. Induction machine with wind turbine model input. [19]

Wind turbine mechanical model (*MOD 2 type*) can use *Wind source* component to specify properties of wind speed, e.g. wind speed mean value, gust, ramp and noise. *Wind turbine governor* is a pitch angle controller and it uses mechanical speed and power output of the machine as inputs. The mechanics (e.g. the turbine masses and shaft properties) are not included in the model. The MOD 2 type wind turbine component is based on rather old academic publications on wind turbines from early 80's, [20] and [21].

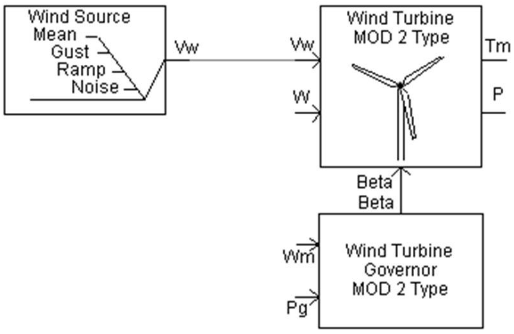


Figure 3. MOD 2 type Wind turbine model. [19]

The MOD 2 component model was tested in [22] with earlier PSCAD/EMTDC version, and now with the current X4 the model operation is correspondingly wrong. The component model (Figure 4) was tested with Bonus 660 kW fixed speed wind turbine parameters (*Figure 5*). The input W, machine (generator) mechanical speed for a 50 Hz, 3 pole pair generator (as rated speed, not considering e.g. the asynchronous generator slip) is 104.719 rad/s (50 Hz/3*2pi). The pitch angle for passive stall turbine is zero. As the Wind Turbine component response to input variable changes is immediate, the P(vwind)-curve for turbine model was created by inputting the wind speed increasing from 0 to 50 m/s. The component outputs Tm and P are plotted in Figure 6. The output power and torque of the turbine are pu-values, of which the maximum ought to be 1.0 pu. As the values increase much higher than 1.0 pu and the maximum of the P-curve is reached only at rather high wind speed, it seems that the Wind Turbine component model is not suitable – nor straight-forward – to be used to represent the wind turbines of today "as is".

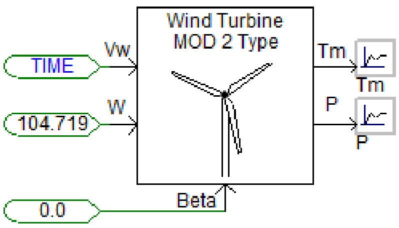


Figure 4. MOD 2 Wind turbine component model setup for testing the component operation.

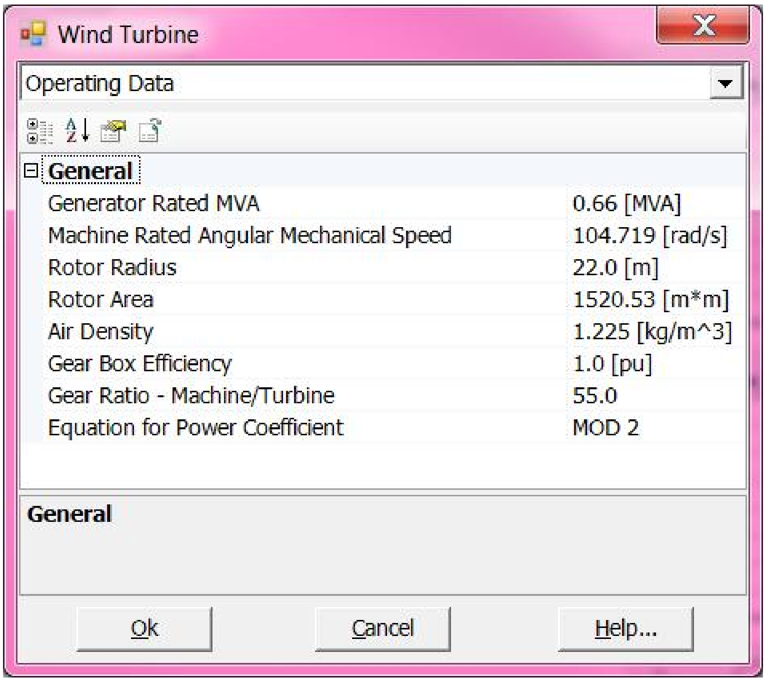


Figure 5. MOD 2 Wind turbine model parameters for testing the component operation with 600 kW Bonus wind turbine.

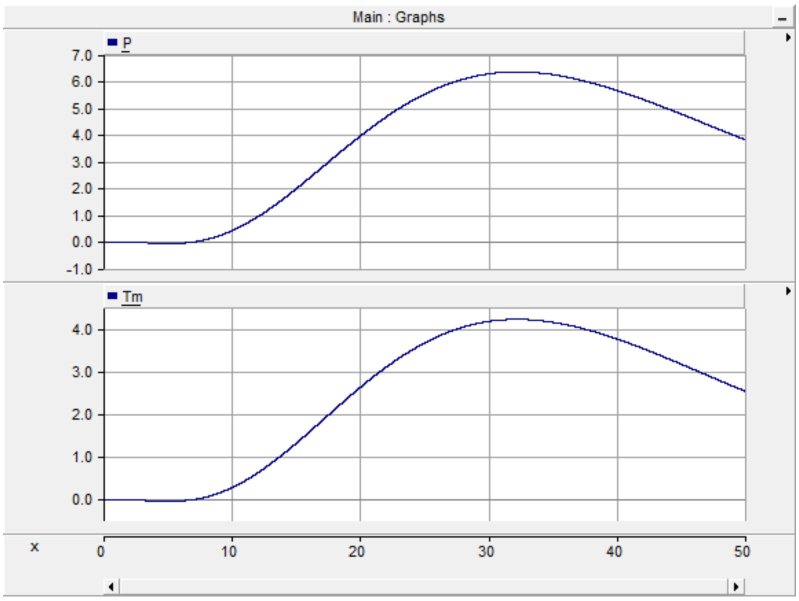


Figure 6. MOD 2 Wind turbine model given output power (P [pu]) and mechanical torque (Tm [pu]) for Bonus 600 kW turbine as function of wind speed [m/s]. The model outputs clearly are not reasonable.

PSCAD example *windfarm_synmc.psc* synchronous machine in Figure 7 is built with generic library components and machine shaft torque T_m is as an input from *MOD 2* wind turbine component. This synchronous machine model does not include power converter, which would be needed if simulations of full power converter equipped with synchronous machine would be of interest to study. Therefore the example model itself is not quite applicable “as is” for wind turbine electrical simulations.

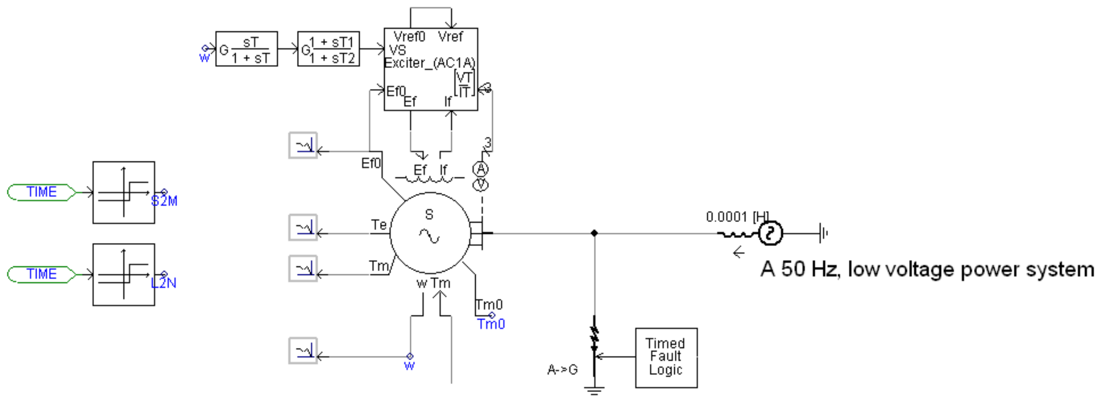


Figure 7. Synchronous machine with wind turbine model input. [19]

Modified *DFIG_V4_November_2010* wind turbine model in Figure 8 is an additional model and it can be downloaded from webpage of PSCAD software [23]. The model documentation supposed to be attached to this model download does not follow with the model package for some reason, but is available from Manitoba HVDC upon request. According to the documentation the DFIG model controller concept is based on [24]. The documentation does not mention if the model has been validated. The downloadable model version seems to contain some minor bugs that need to be corrected before it can be even run (e.g. variable names). It is a full scale model with rotor circuit converter and crowbar protection. The model represents a single 2 MW DFIG wind turbine initially (although the “Wind park” component in the model might imply otherwise).

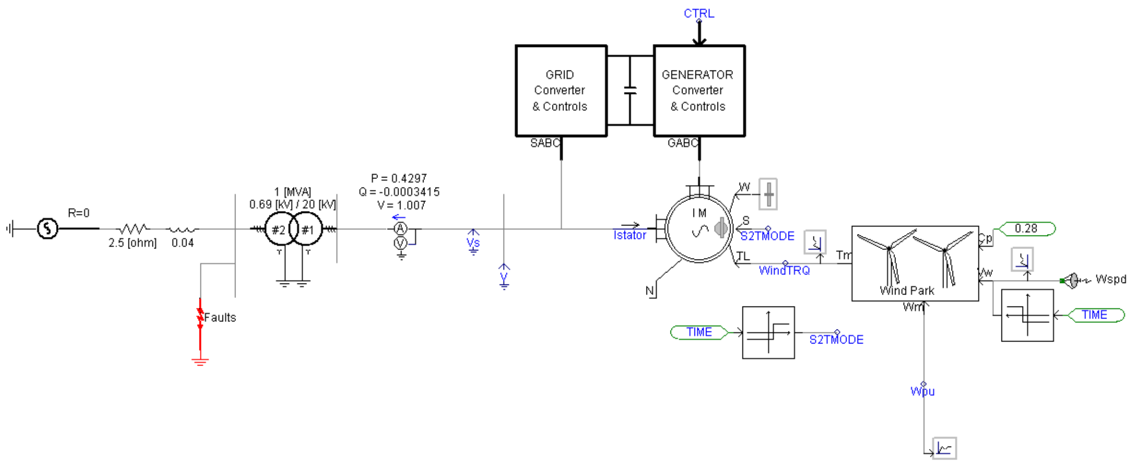


Figure 8. Modified PSCAD-model "Wind farm, vector controlled doubly-fed induction generator" in package DFIG_V4_November_2010. [23]

Some extensive or further reporting of wind turbine simulations with PSCAD/EMTDC can be found e.g. in [25, 26].

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

7 Wind turbine and farm model validation data

7.1 Fixed speed wind turbine model measurement data

For fixed speed wind turbines there is more measurement data available, e.g. VTT has been involved in carrying out disturbance measurements at Olos wind farm, as well as has access to some other similar measurement data from different locations and wind turbines. These data are commonly measurements of voltage dip(s) in the grid, where the phase voltages and currents of the wind turbine are measured at different sampling frequencies. The data usually contains a short period of pre-fault situation, and continues after a short period after the fault (e.g. a few seconds) so that the wind turbine response to the grid fault is seen. [27, 28, 29] These data has been used for validation of fixed speed wind turbine models, e.g. [30, 31, 32].

7.2 Full power converter equipped wind turbine measurement data

VTT has carried out disturbance measurements with ABB in a small wind farm consisting of full power converter equipped wind turbines [33]. The measurements were done to be triggered of disturbance situations in the grid, i.e. voltage dips. Measurements were done and triggered separately of a single wind turbine and the whole wind farm. The phase voltages and phase currents were measured at 2 kHz sampling for 1.54 second measurement period with 0.5 s of pre-triggering data.

The wind turbines in the measured wind power plant were not equipped with FRT-operation (due to grid connection requirements), but according to the disturbance measurements, the wind turbines did not disconnect immediately in case of a relatively large voltage dip.

This measurement data could be used for validation of the full power converter equipped wind turbine models, and identification of generic model parameters for one wind turbine (certain manufacturer and model). It could be used also for assessment of the correspondence of the turbine common parameters vs. generic model parameterizing features, as well as the parameterized generic model operation/response in fault situation comparison to disturbance measurements of actual operation under fault incident.

7.3 DFIG wind turbine measurement data

In an Elforsk report [34] there are described measurements carried out for a 2 MW DFIG wind turbine in order to obtain measurement data for fault ride-though ability evaluation. The measurement data was also used for PSCAD/EMTDC wind turbine model validation. According to [34], the measurements and the constructed generic DFIG wind turbine model showed fairly good agreement.

These measurement data can also be available for VTT for model validation purposes.

8 PSS/E generic model testing and evaluation

There are two essential features and requirements for generic wind turbine models to be looked at depending on the starting point and the needs of the model:

1. The model and model parameterisation should represent the typical (if this can be even considered possible) wind turbine behaviour and characteristics of the respective wind turbine type. This is for the simulation cases where a *typical wind turbine model* is needed, and when only the wind turbine category (wind turbine type according to the standard, see chapters 3 and 4) and the wind turbine type itself (manufacturer, type, size etc.) is not known.
2. The model ought to be the possible to be parameterized so that it would represent a *specific wind turbine* (i.e. by certain manufacturer, type, size, control settings etc.) characteristics and behaviour in simulations.

There are supplied wind turbine models for PSS/E for the four typical wind turbine types as shown in Table 3. PSS/E generic wind turbine models were tested in order to

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

The test system shown in Figure 9 was used for all PSS/E model test simulations described in this chapter. The wind turbine model was connected to the bus 104, and a fault of 250 ms duration was injected in bus 102 creating a large voltage dip also at wind turbine bus.

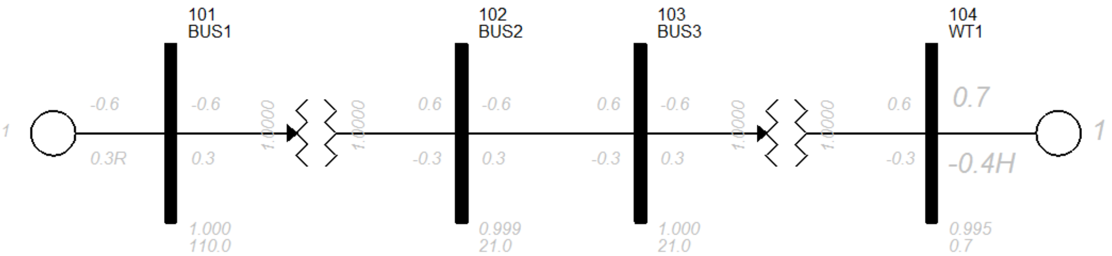


Figure 9. The test system for PSS/E generic wind turbine model testing.

The models were tested for several features and some of the most interesting findings and observations are presented in the following sections.

8.1 Type 1 model

The Type 1 generic model was parameterized for Bonus 600 kW wind turbine, of which there has been disturbance measurements carried out, as well as PSCAD/EMTDC model validation done, described in [22]. The simulation results, i.e. voltage at wind turbine bus, active power and reactive power, are shown in the Figure 10-Figure 12.

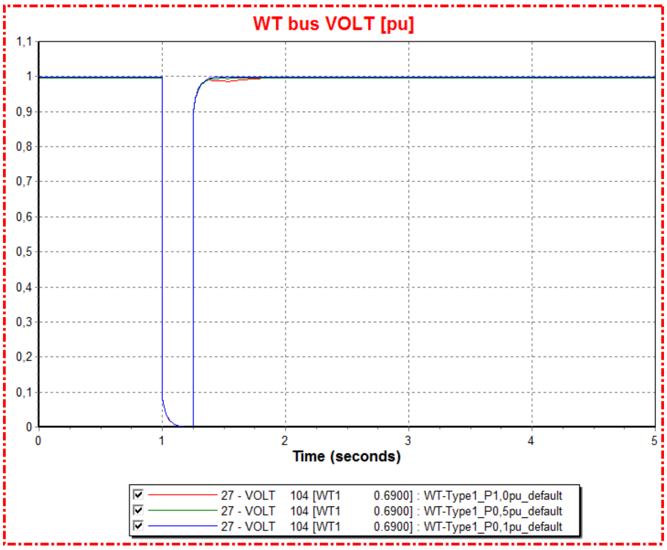


Figure 10. Voltage at wind turbine bus. Type 1 generic model parameterized for Bonus 600 kW wind turbine.

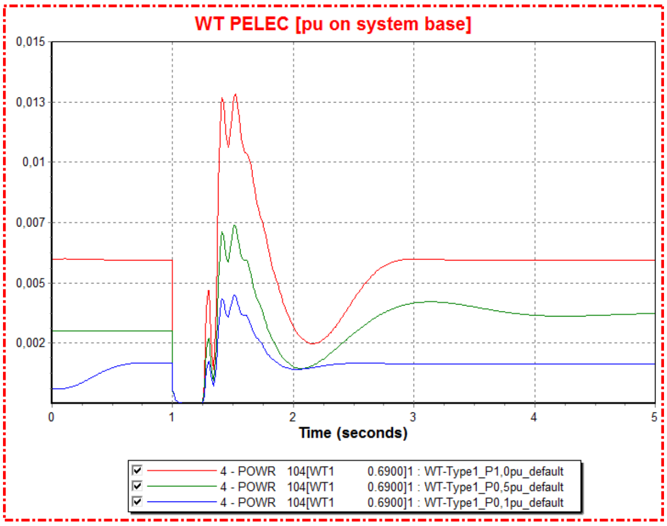


Figure 11. Wind turbine active power response to voltage dip with different initial operating stages of wind turbine nominal power. Type 1 generic model parameterized for Bonus 600 kW wind turbine.

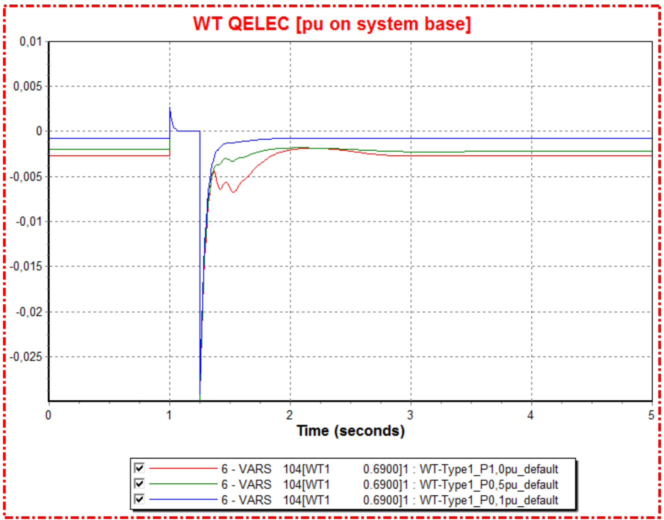


Figure 12. Wind turbine reactive power response to voltage dip with different initial operating stages of wind turbine nominal power. Type 1 generic model parameterized for Bonus 600 kW wind turbine.

For comparison to the validated PSCAD/EMTDC model in [22], the active power response at different wind turbine initial operating stages of nominal active power of the PSCAD/EMTDC model are shown in Figure 13.

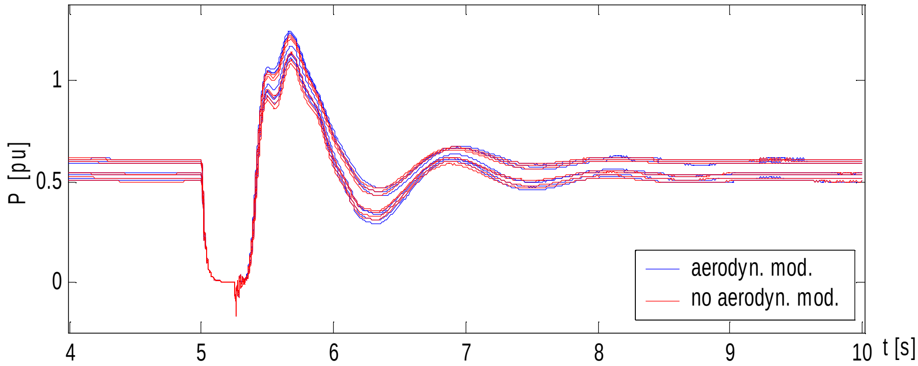


Figure 13. PSCAD/EMTDC Bonus 600 kW fixed speed wind turbine model simulation active power response to voltage dip. Different initial wind turbine operating stages, and comparison of considering and neglecting the aerodynamic model. [22]

The PSS/E Type 1 generic model parameterized for Bonus 600 kW wind turbine seems to give quite good – although not exact – correspondence with a validated PSCAD/EMTDC model.

8.2 Type 3 model

The Type 3 generic PSS/E model is parameterized by default for GE 1.5 MW DFIG wind turbine. In the PSS/E manuals, the Type 3 generic model description and default values suggest single-mass representation for this generic model. Also GE does not recommend using two-mass representation, although provides parameters for two-mass system as well. The single-mass and two-mass parameterization of the Type 3 generic wind turbine model were compared. The simulation results, i.e. voltage at wind turbine bus, active power and reactive power, are shown in the Figure 14-Figure 16.

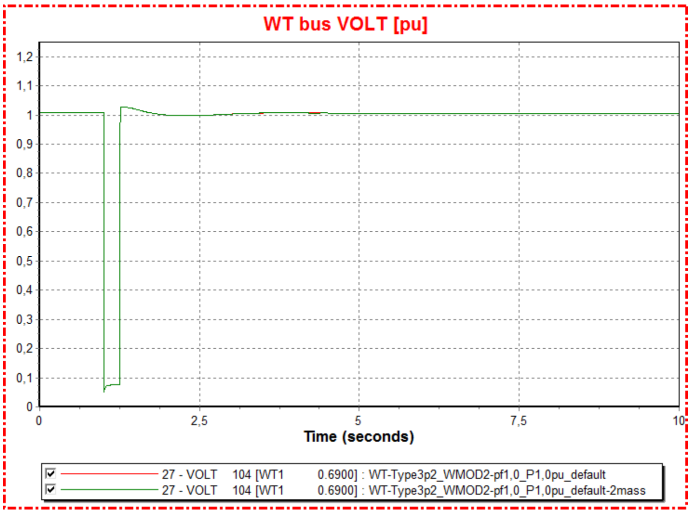


Figure 14. Voltage at wind turbine bus. Type 3 generic model parameterized for GE 1.5 MW wind turbine (default).

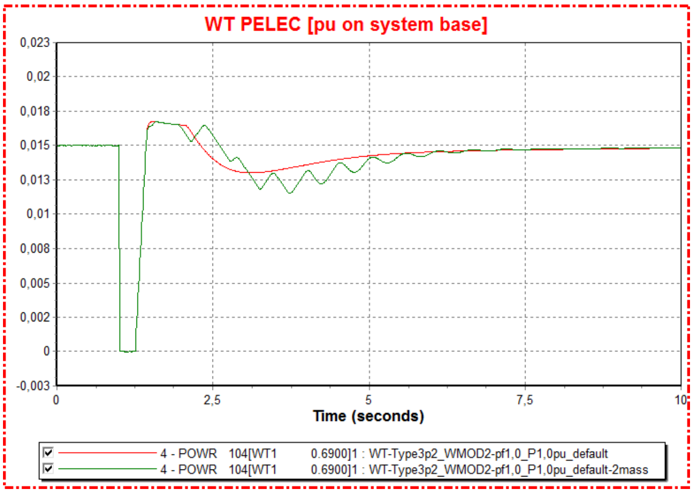


Figure 15. Wind turbine active power response to voltage dip with single-mass model (default) and 2-mass model representation. Type 3 generic model parameterized for GE 1.5 MW wind turbine (default).

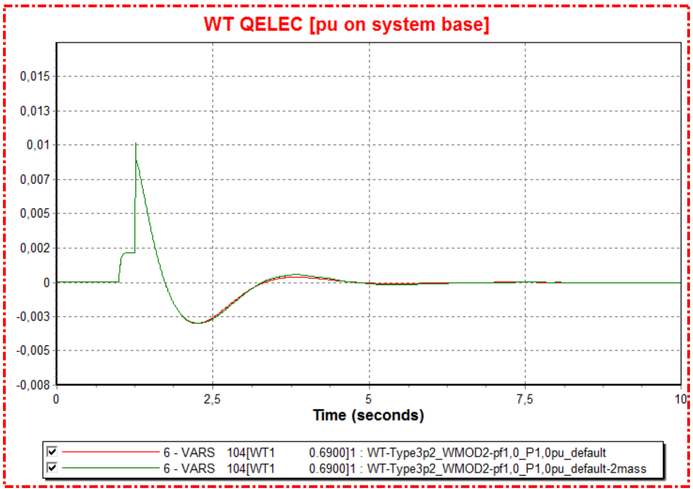


Figure 16. Wind turbine reactive power response to voltage dip with single-mass model (default) and 2-mass model representation. Type 3 generic model parameterized for GE 1.5 MW wind turbine (default).

The 2-mass and the recommended default single-mass representation of the Type 3 generic PSS/E wind turbine model parameterized by default for GE 1.5 MW wind turbine seem to give slightly different active power response.

These simulation results were compared visually to the DFIG wind turbine model validation data presented in [34] of 2 MW Vestas DFIG wind turbine. It is difficult to say if there is correspondence between the measurement data, although the wind turbine reactive and active power response to voltage dip does not seem remarkably different. The PSS/E Type 3 model ought to be parameterized and validated with Vestas 2 MW wind turbine parameters and data for further analysis of the PSS/E Type 2 generic model.

8.3 Type 4 model

There are two Type 4 generic wind turbine models available with PSS/E. One of them is parameterized by default for GE 2.5 MW and the other for Siemens 2.3 MW full power converter equipped wind turbines. These two default parameterized generic PSS/E models are compared to each other. The simulation results, i.e. voltage at wind turbine bus, active power and reactive power, are shown in the Figure 17-Figure 19.

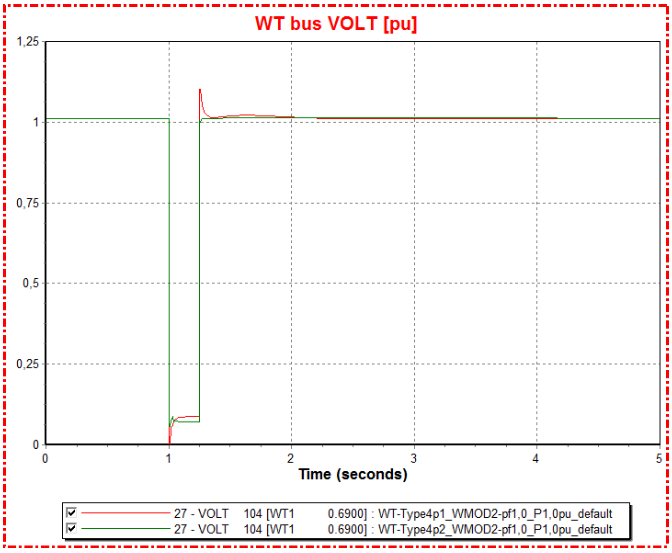


Figure 17. Voltage at wind turbine bus. Type 4 generic models parameterized for GE 2.5 MW and Siemens 2.3 MW wind turbines (default).

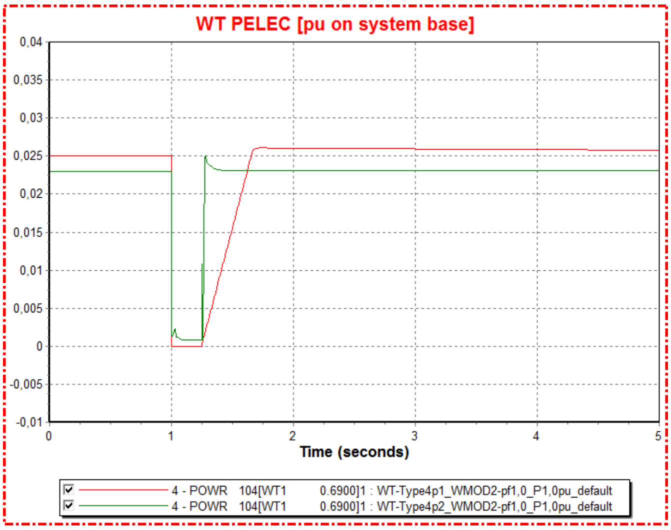


Figure 18. Wind turbine active power response to voltage dip. Type 4 generic models for GE 2.5 MW (default parameters) and Siemens 2.3 MW wind turbines (default parameters).

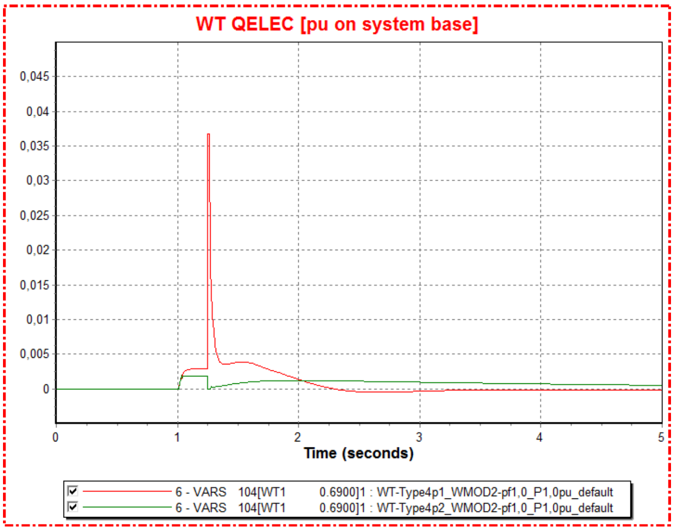


Figure 19. Wind turbine reactive power response to voltage dip. Type 4 generic models for GE 2.5 MW (default parameters) and Siemens 2.3 MW wind turbines (default parameters).

The two “generic” Type 4 wind turbine models seem to have quite many differences in responses to voltage dip. There are actually two different models (see Table 3) and apparently they have different characteristics, and it may be that all the characteristics are not possible to be modeled with both models. The more significant differences are in reactive power response to voltage dip. Active power response can be quite easily adjusted by time constants that are of different magnitude for GE 2.5 MW and Siemens 2.3 MW models.

The models could be parameterized and simulations compared to the available measurement data described in section 7.2 to further testing and analysis of the models.

9 Ancillary services

A definition of ancillary services in this context is to maintain integrity, stability and power system quality. Ancillary services (AS) are needed to keep the system within operational limits and to recover the system in case of disturbance or failure. It can be provided by generators, controllable loads and network devices. Grid code requires some of the ancillary services but some of AS are procured as needed by TSO or DSO. In Figure 20 ancillary services are divided into four categories which are overlapping in some respects. [37]

Voltage is a local measure and it is influenced by reactive power. Voltage differs in every system node and it is recommended to produce reactive power close to consumers in order to avoid unnecessary transmission losses. Three main operating tools are: preventing unnecessary transit of reactive power, new network assets to support active and reactive power transit, and balancing reactive power generation and consumption in the voltage controlled nodes of the system. [37]

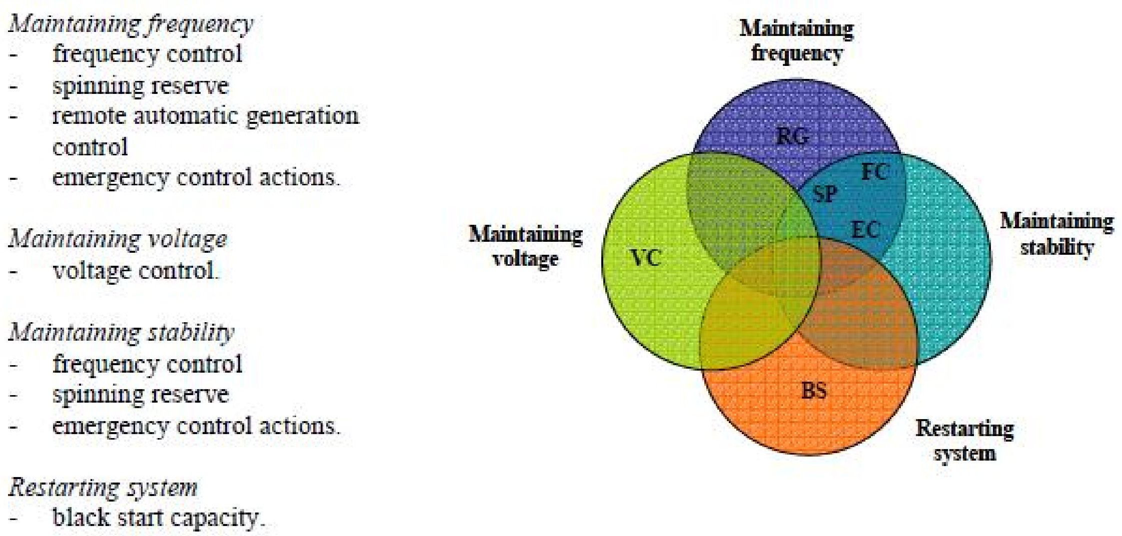


Figure 20. Ancillary services categories. [35]

There are two targets of voltage control: voltage profile management including minimisation of the system active power losses (steady-state), and maintaining voltage stability (dynamic). Reactive source can be too far or of insufficient capacity to prevent slow voltage collapse or limit its depth and extension. The main factor causing voltage instability is the inability of the power system to locally meet the demand. That is why for operational, economic and security reasons variable generation should take part in providing ancillary services. This also means that ancillary services may provide an additional commission or payments depending on who will provide the ancillary services. [37]

9.1 Methods and cost structure

Wind turbines will provide ancillary services in the future when percentage of wind energy production increases of whole energy production. Especially on times of high wind power production when conventional generators are at low production level.

Possible methods to limit the effects to the grid in case of local voltage collapse are to limit load in particular node and/or balance reactive power consumption in that area.

Additional reactive power sources are needed in heavily loaded nodes/buses in case of high RES penetration at the distribution level to ensure that adequate voltage support is maintained. While voltage instability is essentially a local phenomenon, its consequences may have a widespread impact in case of voltage collapse. Voltage and transient stability issues are interrelated and same mitigation measures apply. [36]

In Table 4 costs of ancillary services are categorized into three groups. Implementing the ability to provide ancillary services creates investment costs. Readiness/availability of ancillary services requires part of the generator production capacity to be reserved for the ancillary services, and there are costs (or loss of income opportunity) related to this. Actual provision of ancillary services creates costs, e.g. the fuel cost relative to energy produced, and increased wear and tear of the unit when used for providing ancillary services. [37]

Table 4. The cost structure for ancillary services.[37]

Ability/capability	**Readiness/holding/availability**	**Utilisation/response**
investment cost related to providing the capability	cost for capacity reserved, opportunity cost loosing energy that cannot be sold	Actual provision of the service, like energy as used with fuel cost
	link to other markets	increased maintenance costs (wear and tear)

9.2 Grid code and voltage support

Grid code or network code contains requirements for capabilities for generators and demand appliances. Generator has to be online and generating at level on which the service can be provided. According to the Grid code, generators are required to support frequency and voltage and this ancillary service has to be controllable. New services are as mentioned in REserviceS report [37]: fast frequency response and ramping margin for frequency support, fast reactive current injection during voltage dips and for post fault voltage control, and islanding services related to restoration. [37]

Definition of voltage control is to maintain power system voltage within the prescribed bounds during normal operation and during the disturbances by keeping the balance of reactive power consumption and generation. Grid components which could absorb and inject reactive power can contribute to voltage control. These components are for example: generators, synchronous compensators, capacitor banks, static voltage controllers, FACTS devices (including unified power flow controller), and tap-changing transformers. [37]

In Figure 21 is shown estimation on how much reactive power capability will change during this decade in the power system of Ireland and Northern Ireland. Changes are the result of RES penetration in specific countries. [36, 37]

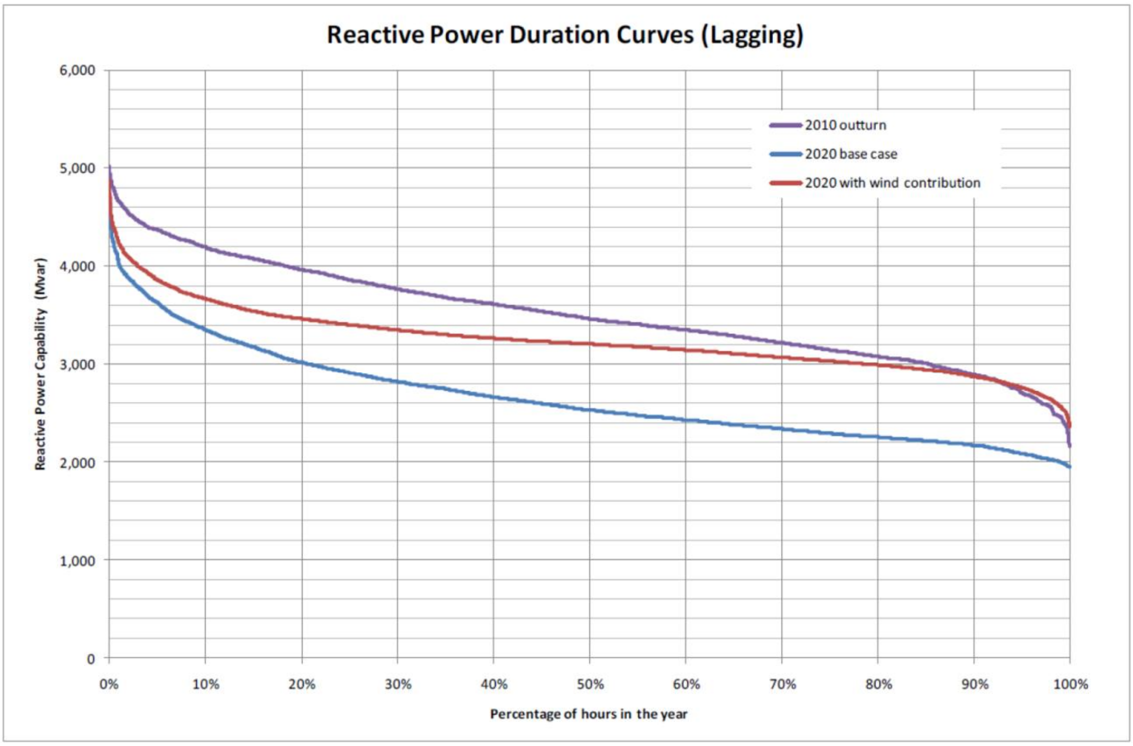


Figure 21. Duration curve for lagging (i.e. feeding to the grid) Mvar capability curve for 2010 against 2020. [38]

ENTSO-E network code requirements for grid connections (ENTSO-E NC RfG) [39] categorizes generators into four groups and three of the four groups are shown in Table 5. For type A generator maximum capacity threshold is 0.8 kW or more. Capacity threshold levels differ between each geographic area because of the characteristics of the local grids. For all other generating module types than Type D, voltage level of connection point is 110 kV or lower. [39]

Table 5. Thresholds for Type B, C and D power generating modules. [39]

Synchronous Area	Maximum capacity threshold from which on a Power Generating Module is of Type B	Maximum capacity threshold from which on a Power Generating Module is of Type C	Maximum capacity threshold from which on a Power Generating Module is of Type D
Continental Europe	1.0 MW	50.0 MW	75.0 MW
Nordic	1.5 MW	10.0 MW	30.0 MW
great Britain	1.0 MW	10.0 MW	30.0 MW
Ireland	0.1 MW	50.0 MW	10.0 MW
Baltic	0.5 MW	10.0 MW	15.0 MW

According to the [39] DSO shall maintain the voltage and reactive power within limits at the connection point to TSO grid and they shall support TSOs in voltage control, also by giving available reactive power reserve information to TSOs. DSO grid is based on radial power flow but in case of high RES penetration there are situations when power flow may be from PVs or wind turbines towards DSOs substation. Both PV and wind turbine unit can provide reactive power compensation and it gives more possibilities to handle voltage profile and transmission losses.

ENTSO-E NC RfG group C Power Park Module U-Q/P_{max}- and P-Q/P_{max}- profiles (see Figure 22 and Figure 23 in Appendix C) are the requirements that most of the local wind farms should fulfil. For example in the Nordic countries Power Park Modules with capacity over 10 MW, are included in group C or D. Inner and outer envelopes in these profiles are guidelines for local power producers. Envelope shape does not need to be rectangular, and position, size and shape of the inner envelope are indicative. EWEAs and EPIAs proposal configures Power Park Module U-Q/P_{max}- and P-Q/P_{max}- profiles with different boundaries (see Figure 24 and Figure 25 Appendix D). Also maximum range of Q/P_{max} and maximum range of steady-state voltage level are slightly modified by region in this EWEAs and EPIAs proposal. [39, 40]

10 Conclusions

Today there seems to be more commonly wind turbine models available for different simulation software as part of the simulation software model libraries. The generic models – four dedicated generic models representing each of the different four commonly categorized wind turbine technology types – seem to be more attractive than need of creating the model from scratch for each different wind turbine (specific by manufacturer and turbine type, size, technology solutions etc.). Even the IEC 61400-27 standard under preparation focuses on the generic models.

The transmission grid or distribution network operator may require the model of a specific wind turbine in their grid for different simulation software. Especially for power system simulations it would be easier for turbine owners/operators/manufactures to provide only the parameters for a generic model of the wind turbine instead of being obliged to build and provide a whole model.

For grid/network owners using the same generic models, it would be an advantage to compare different wind turbines and their performances when using the same models only with characteristic parameters – as is often the case with conventional power production units – and the models would not be any more as black-box type as possibly would be with manufacturer provided models with their individual tricks and procedures needed in running the simulations. In addition the generic model itself, as well as along with experience on using these models, the influence of different parameters and their values will become better known. This may contribute in developing e.g. the requirements to be set for wind turbines, as well as help identifying the possibilities of utilising wind turbines to help the power system (e.g. identifying that certain parameter change by certain magnitude could improve the power system reliability in such-and-such extent).

The PSS/E generic wind turbines models that are provided with the software, were tested and the test simulations with voltage dips are shown in this report. The models are provided with default parameters, and some of the models are related to specific wind turbines, i.e. wind turbine manufacturer and its specific wind turbine model. It is not totally clear under which terms and in which degree these PSS/E models are "generic", i.e. if they represent typical (generic) wind turbine operation of each wind turbine type category (i.e. DFIG, full power converter equipped wind turbine etc.) and on the other hand in case the models can be parameterized for all, or at least most of, the existing wind turbines.

Ancillary services are needed in electric network operation. Some of those services are set as requirements to generators (e.g. ENTSO-E network code) and power production units, and some could be optional services procured by the network operator as needed. There incur costs for generating units related to e.g. implementation of the ability of provision, and usage of ancillary services that need to be covered. Typical ancillary services that are relative to distributed generation wind power are related to voltage control issues.

Appendix A: List of PSCAD component model libraries

List of component model libraries related to wind turbines:

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

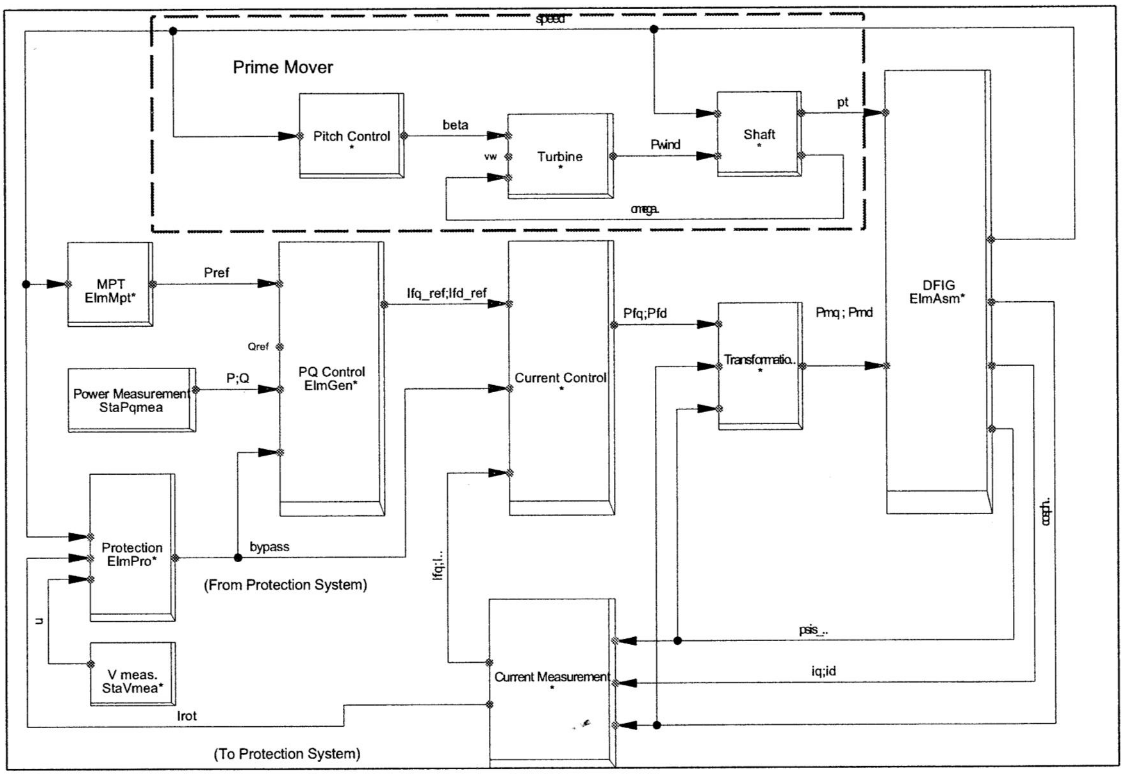
List of reports related to wind turbine component model libraries:

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

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

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

Appendix B: DIgSilent DFIG generator model overview



Appendix C: ENTSO-E NC RfG PU curves of a power park module

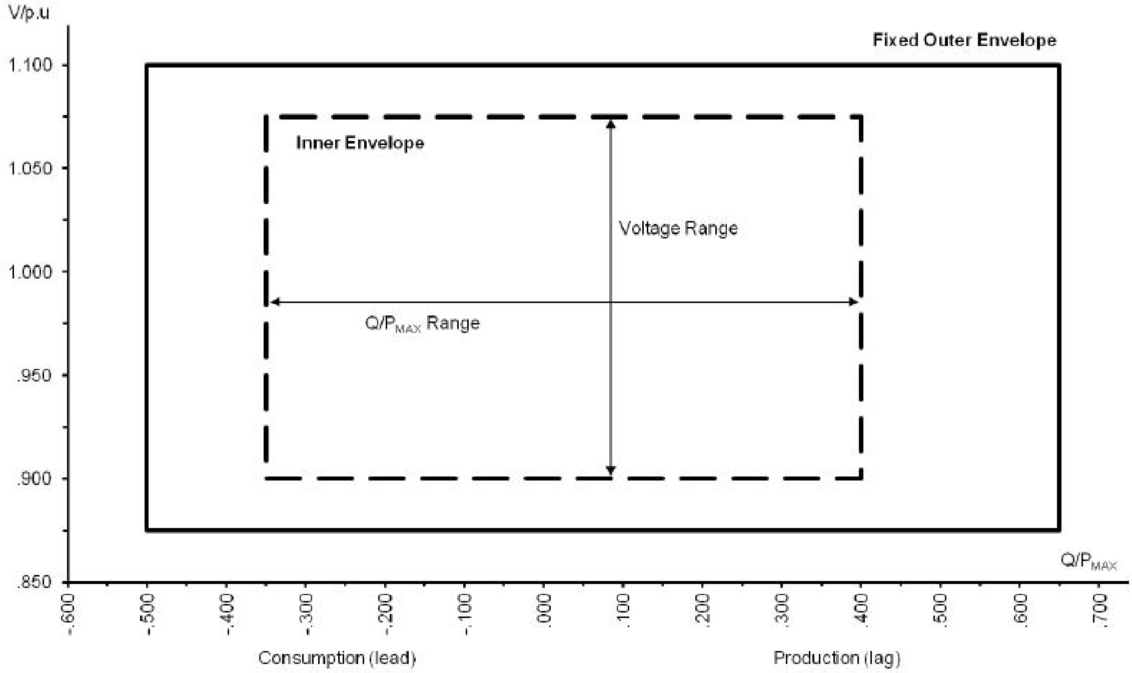


Figure 22. U-Q/P_{max}- profile of a Power park module. [39]

Requirements of type C Power Park Modules: U-Q/P_{max}-profile of a Power Park Module. The diagram represents boundaries of a U-Q/P_{max}-profile by the Voltage at the Connection Point, expressed by the ratio of its actual value and its nominal value in per unit, against the ratio of the Reactive Power (Q) and the Maximum Capacity (P_{max}). The position, size and shape of the inner envelope are indicative. [39]

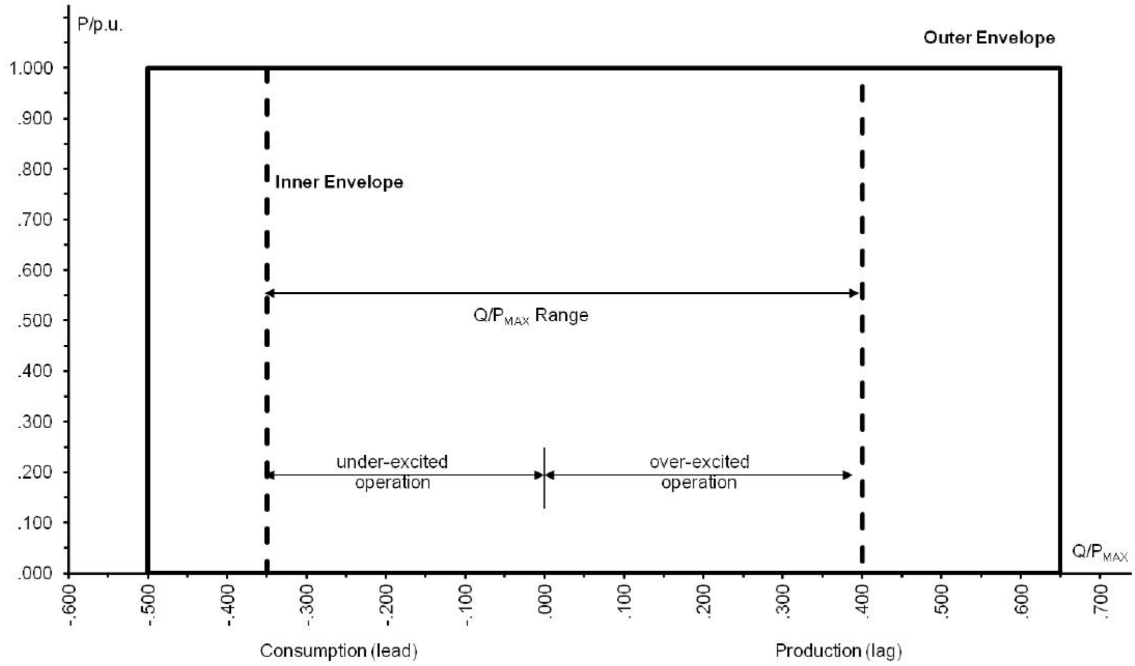


Figure 23. P-Q/P_{max}- profile of a Power park module. [39]

Requirements of type C Power Park Modules: P-Q/P_{max}-profile of a Power Park Module. The diagram represents boundaries of a P-Q/P_{max}-profile at the Connection Point by the Active Power, expressed by the ratio of its actual value and the Maximum Capacity in per unit, against the ratio of the Reactive Power (Q) and the Maximum Capacity (P_{max}). The position, size and shape of the inner envelope are indicative. [39]

Appendix D: EWEAs and EPIAs comment to ENTSO-E RfG network code PU curves

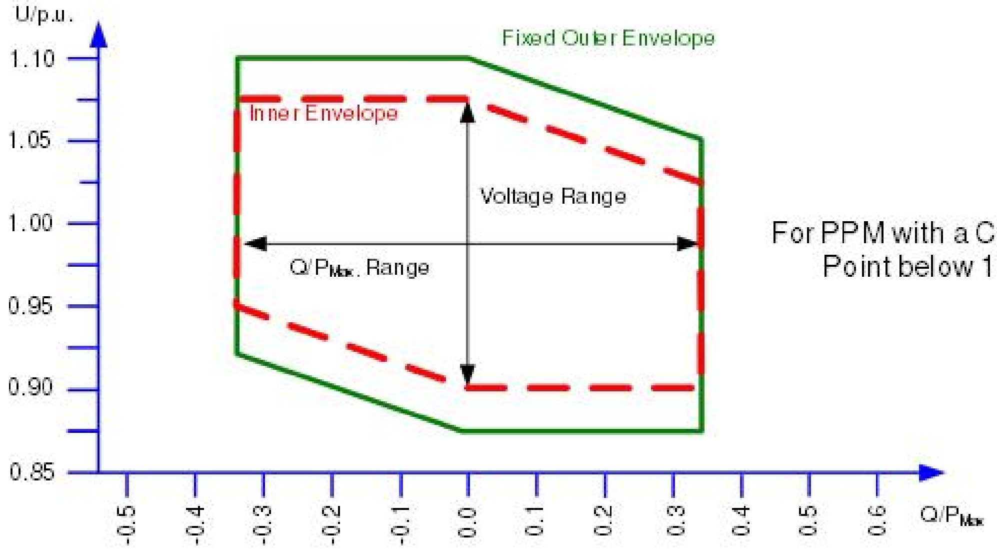


Figure 24. EWEAs and EPIAs comment to U-Q/P_{max}- profile of a power park module. [40]

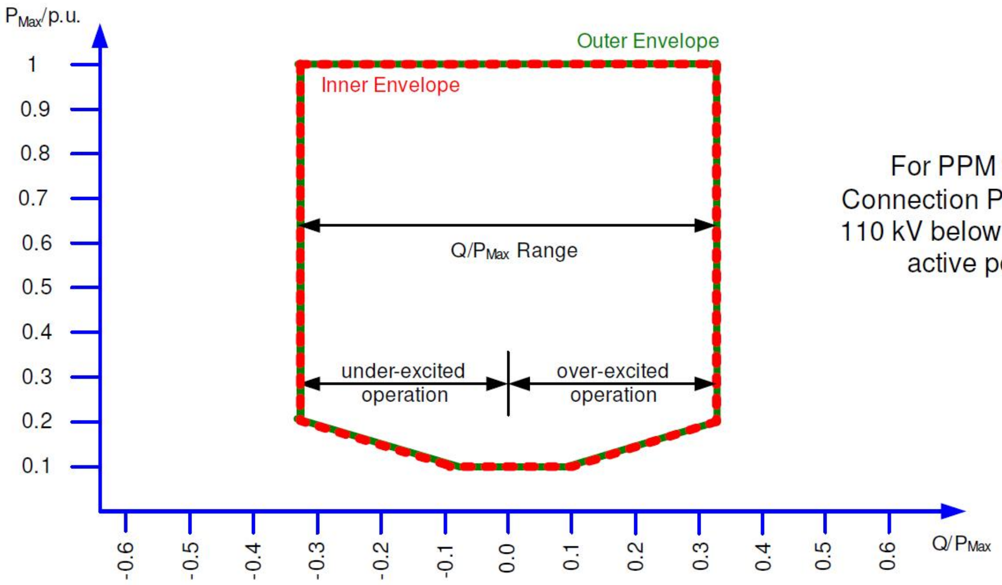


Figure 25. EWEAs and EPIAs comment to P-Q/P_{max}- profile of a power park module. [40]

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