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Type IV Wind Turbine Model

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Summary

This document is created as part of the EaseWind project. The goal of this project is to develop and investigate new control features for primary response provided by wind power plants. New control features as inertial response, synchronising power and power system damping are of interest to EaseWind project to be incorporated in the wind power plant level.

This document describes the Type 4 wind turbine simulation model, implemented in the EaseWind project. The implemented wind turbine model is one of the initial necessary steps toward integrating new control services in the wind power plant level. In the project, this wind turbine model will be further incorporated in a wind power plant model together with the implementation in the wind power control level of the new control functionalities (inertial response, synchronising power and power system damping). For this purpose an aggregate wind power plant (WPP) will be considered. The aggregate WPP model, which will be based on the upscaling of the individual wind turbine model on the electrical part, will make use of an equivalent wind speed.

The implemented model follows the basic structure of the generic standard Type 4 wind turbine model proposed by the International Electrotechnical Commission (IEC), in the IEC61400-27-1 Committee Draft for electrical simulation models for wind power generation, which is currently under review, [1]. The Type 4 wind turbine model described in this report includes a set of adjustments of the standard Type 4 wind turbine model in order account for the dynamic features of interest to EaseWind project.

The document presents a short overview of the overall structure of the wind turbine model. Descriptions of individual submodels as well as some preliminary simulation results are included to illustrate the performance of the model.

Introduction

The goal of EaseWind project is to investigate and develop new primary control features for ancillary services provided by wind power plants, which are described in [1] The project is focusing on inertial response, synchronizing power and on power system damping (PSS like functionality) as new primary control functions and response actions at wind power plant level. The goal is to implement and integrate these new control functionalities with default controls already implemented in the wind power plant level like frequency control, active power control, reactive power control and voltage control.

An overview on the signals between the wind power plant (WPP) level and the wind turbine (WT) level is illustrated in Figure 1. An aggregate model will be used for the wind power plant. The aggregation method consists of an aggregation of the electrical system, while the mechanical part of the aggregated model will be modelled as for one individual wind turbine. An equivalent wind speed, which will incorporate the effects of temporal and spatial correlation between the individual wind turbines, will be calculated as an average of the individual wind turbine speed time series. The individual wind turbine time series will be generated using CorWind model [2], developed by DTU Wind Energy.

The wind power plant (WPP) level interacts with the wind turbine control level through a set of signals, i.e. power set points and status feedback signals, in order to provide the relevant grid support. Depending on the actual grid status, the system operator issues specific set points to the wind power plant controller. This controls the power production from the whole wind farm by generating power set points to each individual wind turbine controller, based on the power system demands, measurements in PCC and feedback status signals from wind turbines.

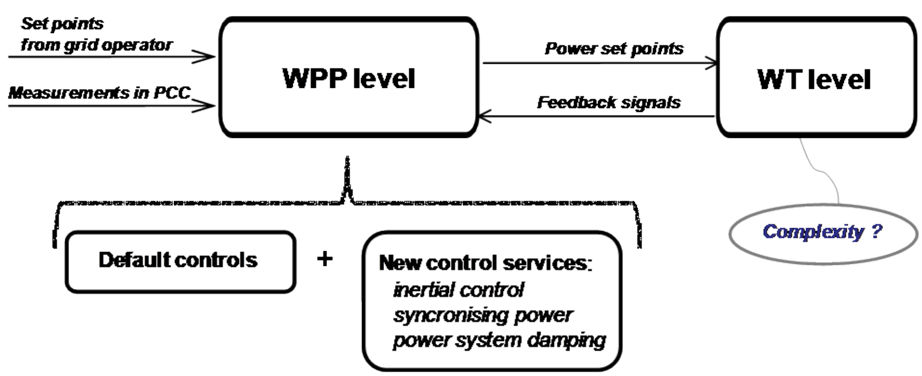

Figure 1: Overview of the wind power plant and wind turbine level.

The first step toward integrating the new control functionalities in the WPP level is to implement a wind turbine model, which accounts for the dynamic features of interest for the targeted ancillary services in the EaseWind project. The complexity of such wind turbine model is of high relevance and it should account on one hand for the dynamic features of interest to EaseWind project and on the other hand be suitable for large scale power system studies, i.e. not requiring long simulation computational time. It is however worth mentioning here that some ancillary services such as power system damping may require a simulation time frame of hundreds of seconds.

A simulation wind turbine model for a variable speed wind turbine with full scale power converter including a 2-mass mechanical model (Type 4B), suitable to reflect the dynamic features of interest to EaseWind project, is proposed and described in this document. This model follows the generic approach proposed by the IEC Committee in the Part 1 of the IEC 61400-27 [3], nevertheless includes additional features, adjustments and extensions of the standard model in order to address the targeted ancillary services in the EaseWind project.

In Part 1 of the IEC 61400-27, the IEC specifies a series of wind turbine generic models for different wind turbine types (Type 1, Type 2, Type 3 and Type 4), as well as validation procedures, which can be applied in power system stability studies i.e. large-disturbance short term voltage stability, rotor angle stability, frequency stability, small-disturbance voltage stability phenomena. The general structure of the generic models for different wind turbine types provided in [3] is illustrated in Figure 2.

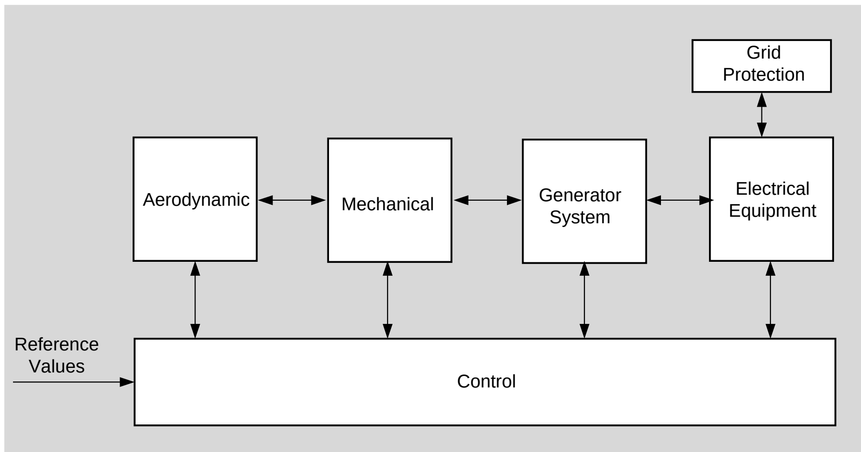

Figure 2: Generic model structure of IEC 61400-27-1 wind turbine electrical simulation models, [3].

The generic models for wind turbines, described in IEC61400-27-1-Part1 [3], are suitable for fundamental frequency positive sequence response simulations during typical events in the power system such as short-circuits, loss of generation or loads, system separation in two synchronous areas etc. Nevertheless, they are not able to reflect wind power plants frequency control capabilities to provide possible future system services like i.e. inertia control, synchronizing power and power system damping. The response of wind turbine standard models and their range of applicability is for example extensively described and analyzed in [4], [5].

By the IEEE definition, a Type 4 wind turbine is a variable speed wind turbine with synchronous or asynchronous generator connected to the grid through a full scale power converter. There are two different models of Type 4 wind turbine described in IEC61400-27-1- [3], namely Type 4A where the aerodynamic and mechanical parts are neglected and Type 4B, which includes a 2-mass mechanical model assuming constant aerodynamic torque. As mentioned before, the attention drawn in this document is on a Type 4B wind turbine model suitable for EaseWind project interest.

Table 1 presents and compares the main features of Type 4B IEC standard wind turbine model, as described in [3], and of a Type4B wind turbine model suitable for interest in the Ease Wind project. Notice that the standard wind turbine model for Type 4B is focusing on short electrical events, like i.e. short circuits. Contrary to Type4 wind turbine model relevant for EaseWind project, the standard model is therefore not intended for studies with wind speed variability. The constant wind speed implies the need only of constant aerodynamic torque and therefore there is no need for aerodynamic model or for pitch control model to be included. Moreover, such wind turbine model with constant wind speed is not able to provide information on available power, which is essential whenever primary control actions from wind turbines are studied, as it is the case of EaseWind project.

Standard Type4B WT model *(can be used in short-circuit events studies)*	**EaseWind Type4B WT model** *(can be used in frequency control studies)*
Constant wind speed ▪ constant aerodynamic torque ▪ no aerodynamic model included ▪ no pitch control needed ▪ no info. included on available power	Dynamic wind speed ▪ variable aerodynamic torque ▪ aerodynamic model needed ▪ pitch control needed ▪ available power information needed
Mechanical model ▪ 2 mass model included	Mechanical model ▪ 2 mass model included ▪ coupling to aerodynamic model *(accounts for the dynamics of rotor speed)* ▪ Any structural mode (i.e.tower model) with eigenfrequencies coinciding with the freq. of interest to the ancillary service algorithms possibly needed
Operation ▪ nominal operation only ▪ derated operation not as option ▪ available power is nominal power	Operation ▪ nominal or derated operation possible ▪ available power calculation needed

Table 1: Comparison between standard model and proposed wind turbine model for Type 4 wind turbine.

As shown in Table 1, information on wind speed variability and available power might be of high relevance whenever implementation and study of new control functionalities, like inertial response and primary frequency control are in focus. It might reflect the limits of wind turbines in specific situations for providing ancillary services. This implies that an aerodynamic model and a pitch control model should be implemented in the wind turbine model relevant for EaseWind project propose in order to account properly for the dynamics and the limits of the rotor speed.

The standard Type 4 wind turbine models described in Part 1 of the IEC 61400-27 [3], are thus not able to reflect wind power plants frequency control capabilities to provide possible future system services like i.e. inertia control, synchronizing power and power system damping. These novel control features will be addressed in Part 2 of the IEC61400-27, where focus will be on generic wind power plant models and on aggregation methods.

Notice that a 2-mass equivalent mechanical model is considered sufficient both for the scope of studies described in the IEC Part 1 document for standard models [3] and for EaseWind project. The two masses correspond to the low speed mass of the turbine and the high speed rotor of the generator. An adequate complex mechanical model is of great significance, as it might reflect some physical limits regarding the possibilities of the wind turbines to provide with active response during events in the power system that affect frequency. Moreover, for the proposed wind turbine model, the coupling between the mechanical model and the aerodynamic model is of high importance, in order to reflect correctly the dynamics of the rotor speed, which might contain information about wind turbine's limits to contribute with inertia control. In this respect, the estimation of the parameters in the mechanical model is also essential. Depending on the results, any structural mode (i.e. tower model) with eigenfrequencies coinciding with the frequencies of interest to the ancillary service algorithms needs to be included in the mechanical model of the proposed wind turbine model in a later stage, but this is an open issue to be investigated. However, validation of structural integrity is not in scope for the present wind turbine model.

Provision of ancillary services under various wind conditions may require a curtailed operation of the wind turbine in order to avoid overloading. However, as the IEC standard Type 4 wind turbine model does include neither an aerodynamic model nor a pitch control model, it is not able to be used in a curtailed mode. It is therefore not suitable for the purpose of the ancillary services addressed in this work.

Table 2 provides a list of the variables, that a wind turbine model, which is relevant for the purpose of the EaseWind project, should account in order to make possible to integrate the new control features as inertial response, synchronising power and power system damping in the wind power plant level. In concordance with Table 1, Table 2 also presents which features are covered or not by the standard Type4B wind turbine model and which adjustments have been done in the model in order to make it relevant for EaseWind project propose.

Identified variables that should be available in EaseWind Type4 wind turbine model			**Standard Type4B WT model**	**Adjustments on standard WT model for EaseWind project**
Wind	** realistic (turbulent)*		%	**turbulent wind** *(in aerodynamic model)*
$P_{available}$	** defined based on power curve*		%	**available power** *(info given by power curve)*
	** depends on wind speed not on WT operation /*			
	** provides limits for inertia control*			
P_{actual}	** limits*		√	**power control loop with power feedback**
	** time constant of power control loop*		√	
	** RMS measurement*		√	
ω_{wtr}	** needs to be seen by the controller*		√	
	** limits*		√	
	** dynamics*	aerodyn.model	%	**aerodyn. model** *(Cp table)*
		2 mass mechanical model	√	
		tower model	%	*(tower model - maybe)*
f_{grid}	** measurement*		√	
I_{gen}	** dynamics*		√	
	** limits*		√	
U_{grid}	** RMS measurement*		√	
	** protection*		√	
	** limits*		√	
θ_{ref}	** pitch control*		%	**pitch control**

Table 2: Adjustments on IEC standard Type4B wind turbine model for EaseWind project propose.

Structure of the simplified/adjusted Type4B wind turbine model

The proposed wind turbine model in this work follows the basic structure of the standard Type 4B wind turbine model proposed by the IEC Committee in the IEC 61400-27-1 [3], but furthermore it includes additional adjustments and features in order to represent wind turbines' active power control capability whenever events in the power system, that affect the grid frequency, occur.

This wind turbine model has as target to reflect correctly the dynamic behaviour of wind power output caused for example by wind speed fluctuations or by changing the active power setpoints in the active power control loop of wind turbines.

Compared to the IEC standard Type 4B wind turbine model, the proposed wind turbine model, includes a sufficiently detailed representation of the turbine's relevant components and control algorithms, allowing implementation of new control functionalities, such as inertial response and primary frequency control. Moreover, the model is built-in in such a way that it allows modifications of the component submodels and of the controls. This may be very useful when other submodels should be considered, like for example when it is necessary to replace the existent mechanical model by one including tower and blade's dynamics.

The extended and adjusted configuration of the standard Type 4B wind turbine model, under focus in this work, is illustrated in Figure 3. The proposed model consists mainly of an aerodynamic model, a pitch control, a mechanical model, a generator system and an electrical control system (including the active power and reactive power control loop). Notice that besides component and control blocks, there are also some additional blocks like wind speed, available power, maximum power point tracking (MPPT) and selection mode blocks.

Figure 3 also depicts the interface signals between the wind turbine model and the wind farm controller. The wind turbine controller receives inputs from the wind farm controller, i.e. like active and reactive power setpoints and overproduction requirement signals. On the other hand, the wind turbine model also provides signal outputs to external wind farm controller, such as generated power and available wind power.

It is important to stress that the mechanical model, the generator static model and the reactive power control model in Figure 3 are identical with those described by IEC for the Type4B wind turbine model in IEC61400-27-1 [3].

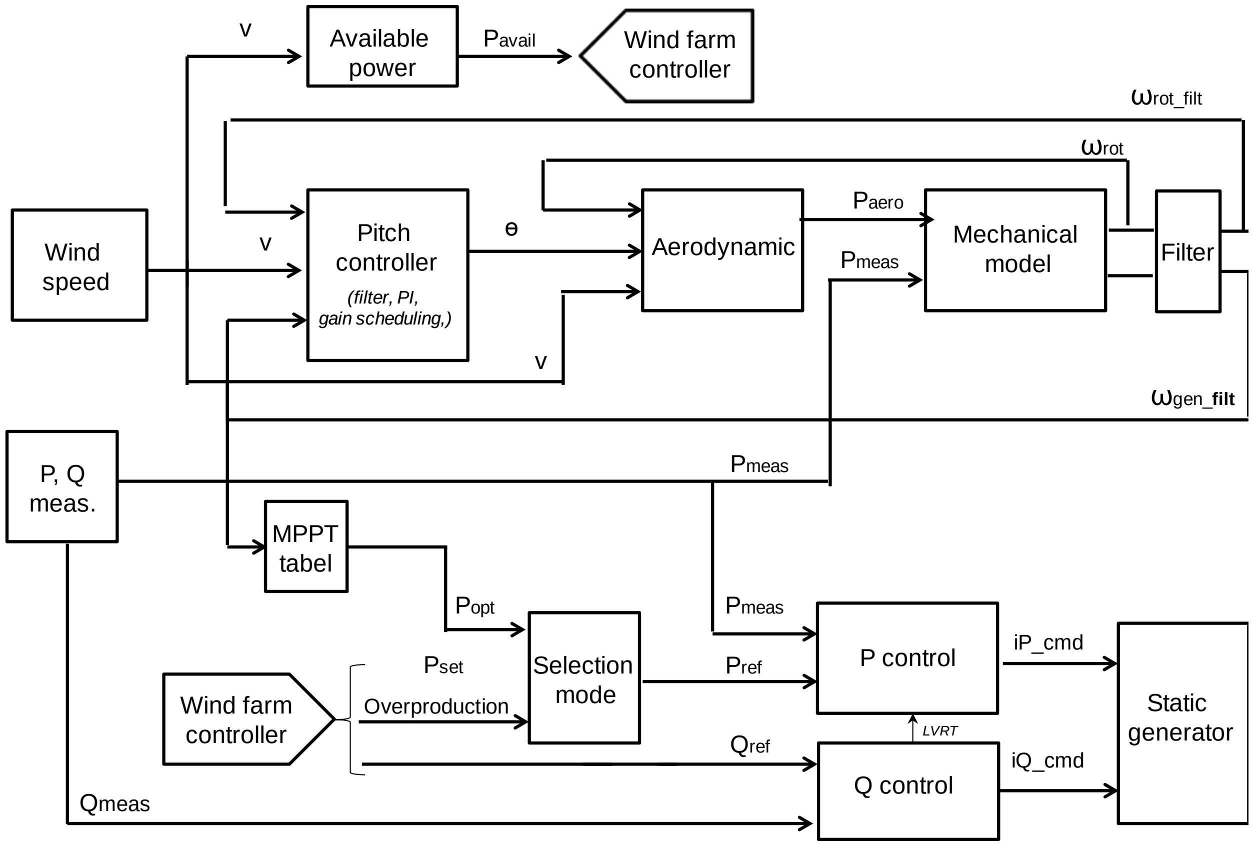

Figure 3: Proposed Type 4B model structure.

Mechanical model

In the mechanical model, the emphasis is put on those parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid, i.e. the drive train. It is worth noticing that an adequate complex mechanical model is of great significance for frequency control studies, as it might reflect some limits regarding the possibilities of the wind turbines to provide active power during frequency events. For example, a mechanical model also including tower dynamics might be used, when the wind turbines' capability to provide an ancillary service like power system damping will be investigated.

The mechanical model is thus represented through a 2-mass model, in order to reflect the torsional shaft oscillations whenever there is a sudden torque imbalance in the mechanical system, as for example due to short circuits, wind gust or change in the active power setpoint of the turbine. The mechanical model, is sketched in Figure 4, where the parameters are the inertia constant of the wind turbine rotor H_{rot} [pu], the inertia constant of the generator H_{gen} [pu], the shaft stiffness k_{sh}[pu] and the shaft damping c_{sh} [pu]. Notice that the aerodynamic and airgap power are inputs to the mechanical system of the model. The airgap power is calculated at the static generator. It is thus equal to the electrical power injected to the grid as no losses are taken into account.

As the shaft is not perfectly stiff, torsional shaft oscillations occur whenever there is a sudden torque imbalance in the mechanical system, as for example during short circuits, wind speed gust or change in the power setpoint by the system operator.

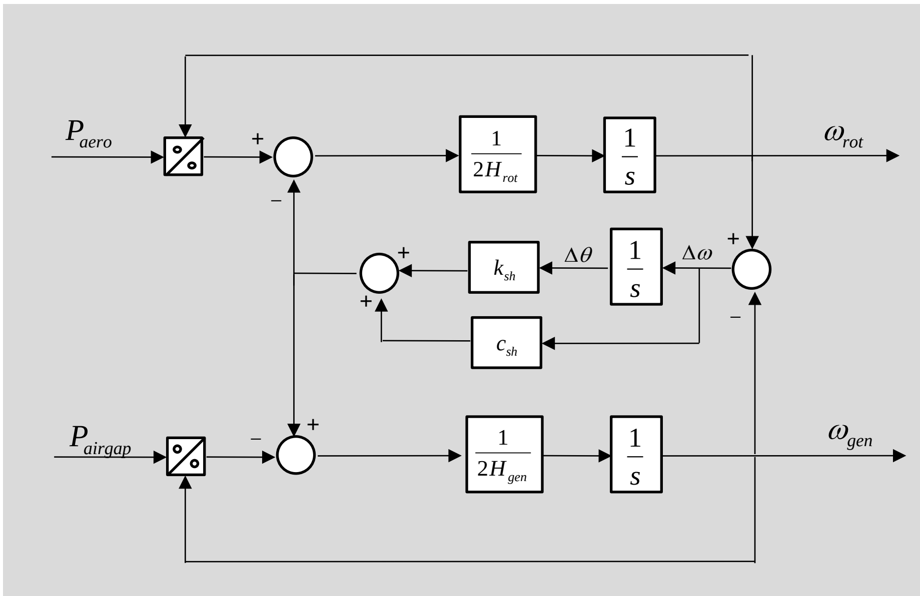

Figure 4: Two mass mechanical model.

Aerodynamic model

As mentioned previously, in addition to the IEC standard Type 4B model, the proposed model also contains an aerodynamic model and a pitch control model.

A simplified aerodynamic model, based on a two-dimensional aerodynamic torque coefficient Cq(θ, λ) table, provided by a standard aerodynamic program, is sufficient to illustrate the effect of the speed and pitch angle changes on the aerodynamic power. This is a quasistatic aerodynamic model which determines the output aerodynamic torque directly from the input wind speed according to:

$$P_{aero} = T_{rot}\ \omega_{rot} = \frac{1}{2}\rho\ \pi\ R^3\ u^2\ \omega_{rot}\ C_q(\theta,\lambda)$$

It is worth noticing that the coupling between the mechanical model and the aerodynamic model is essential in order to account for a correct representation of the dynamics of the rotor speed. These dynamics might contain relevant information about wind turbine's limits to contribute with ancillary services, like inertia control.

Pitch controller

The pitch angle control is realised by a PI controller with antiwind-up, using a servomechanism model with limitation of both the pitch angle and its rate-of-change, as illustrated in Figure 5. The pitch angle controls the generator speed, i.e. the input in the controller is the error signal between the measured generator speed and the reference generator speed. The pitch angle controller limits the rotor speed when the nominal generator power has been reached, by limiting the mechanical power extracted from the wind and thus restoring the balance between electrical and mechanical power. A gain scheduling control of the pitch angle is implemented in order to compensate for the nonlinear aerodynamic characteristics.

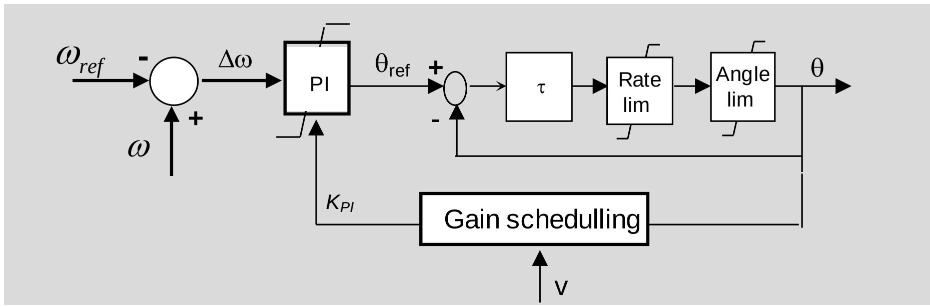

Figure 5: Pitch angle control.

The gain scheduling control, illustrated in Figure 6, is necessary in order to account for the non-linearity of the Cq curve. The sensitivity dP/dθ of the Cq curve actually changes with the operational point. Though, it is desirable to have a pitch control which always provides the same performance, regardless of the actual working condition. Notice that the sensitivity dP/dθ is calculated making use of the power coefficient curve. This makes the calculation all over the characteristic possible and relatively straightforward.

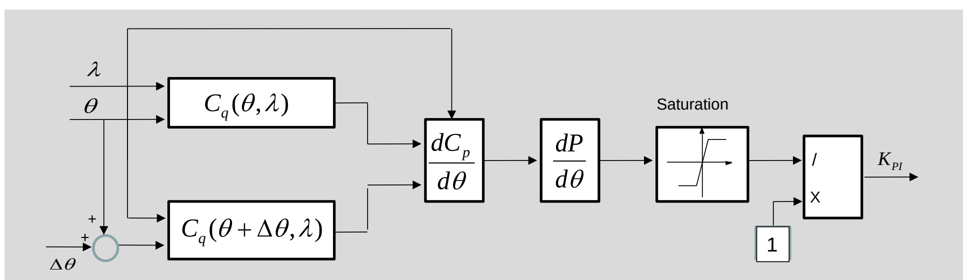

Figure 6: Gain scheduling control.

It is important to notice the presence of a saturation block, which is aimed at preventing the sensitivity from becoming nil or positive, that would lead to an infinite or positive scheduled gain. This may happen when the turbine is working in power maximization mode, that is at the maximum available C_P, when the derivative of the C_P characteristic with respect to the pitch angle θ may be zero or even positive, due to the working point and to the actual non-continuity of the available C_P curve.

Generator set model

The generator system in Figure 3 is modeled via a static generator component, including a current limiter. The static generator is typically used in any kind of static (no rotating) generator modeling. In Type 4 wind turbines the response, seen from the grid side, is determined by the full converter attached to the generator allowing for use of the static generator component. A static generator model can typically support both a current source and a voltage source model. In the present implementation, a current source model is used.

Figure 7 presents the configuration of the static generator and of the generator reference currents model. Notice that the current source model is considered ideal, therefore the current controller is not included.

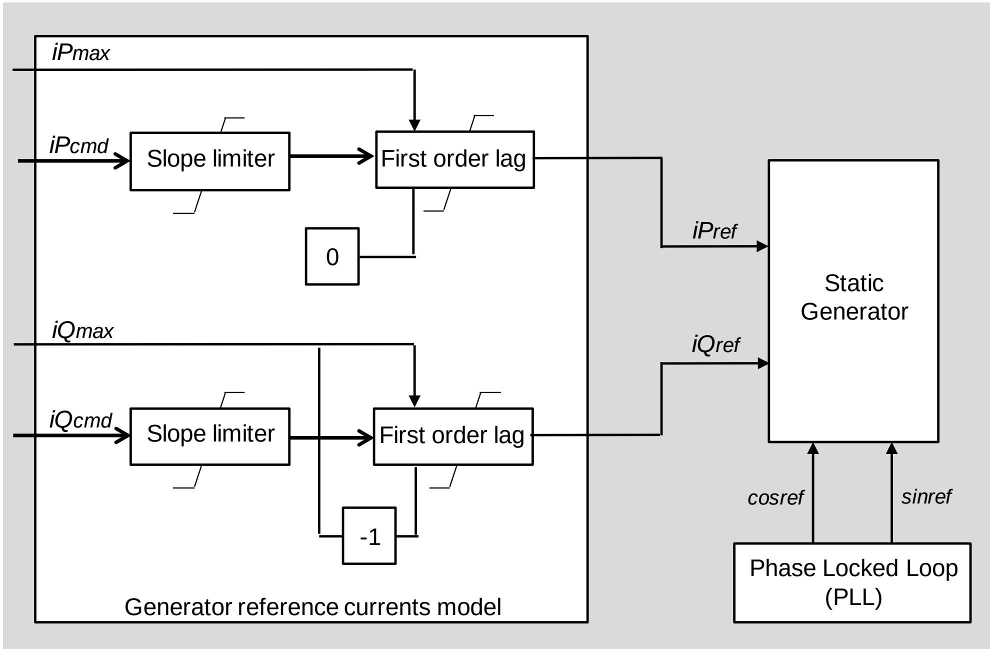

Figure 7: Generator set model (generator reference model and static generator)

Active power control

The active power control loop is illustrated in Figure 8. Contrary to the active power control loop described in the IEC Type4B wind turbine model [3], where the generator speed is used as input in order to account for the electromechanical oscillations especially during faults, the active power controller implemented in this work uses as input the error signal between the measured power in PoC and the power reference[1]. The power feedback has to be included in the wind turbine model to account for dynamic features of interest to EaseWind project. The LVRT signal in Figure 8, calculated in the reactive power control block (see Figure 10) is used to freeze the state of the PI controller, when low voltage is detected.

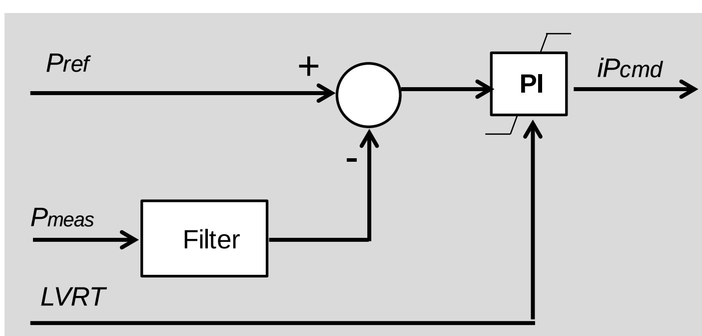

Figure 8: Active power control loop.

1 The power will be measured in the turbine terminals, instead of PoC, when plant controller will be included.

MPPT look up table and selection mode blocks

Figure 9 illustrates the inputs and ouputs signals of the maximum power point tracking (MPPT) lookup table and the selection mode block.

The maximum power point tracking (MPPT) lookup table provides the optimal aerodynamic power by keeping the turbine to work at maximum power coefficient Cp, until the nominal rotational speed is reached.

The selection mode block has as inputs the optimal power from MPPT block, the power setpoint and the "overproduction" signal from the wind farm controller. If overproduction=0, the turbine is required to operate with overproduction during a limited period of time. When no overproduction is required (i.e. overproduction=1), the power reference is given by the minimum between the optimal power and the power setpoint coming from the wind farm control. When the power setpoint P_{set} is lower than the optimal power given by the MPPT, the turbine operates in curtailed mode. If an overproduction is imposed, the power reference is directly given by the power setpoint coming from the wind farm controller.

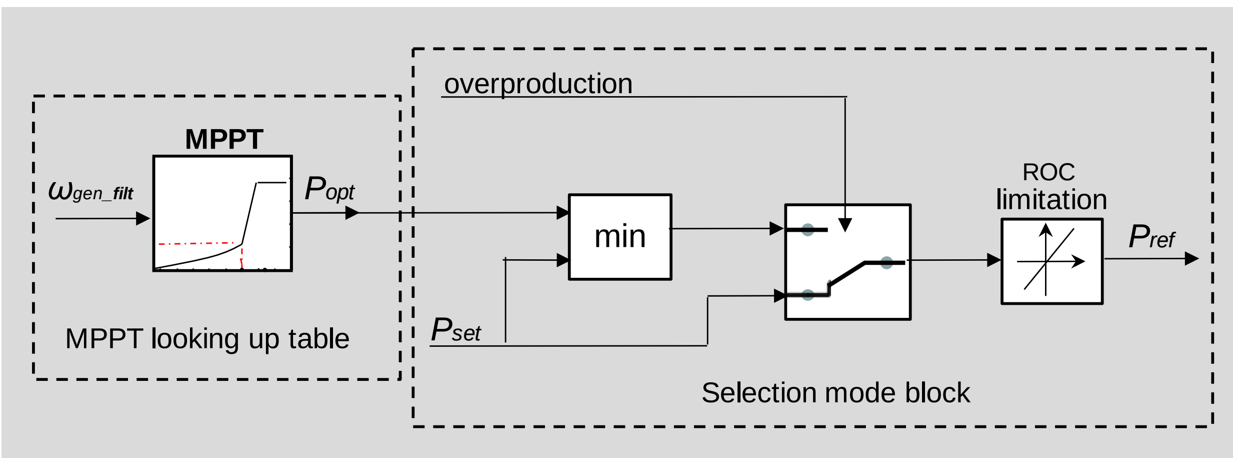

Figure 9: MPPT lookup table and selection mode blocks.

Notice that a rate-of-change limitation on the power reference might be used, as it is shown in the diagram. It may not be needed for the control, but is anyway inserted to provide some flexibility. The simulations presented in this document are performed with a deactivated ROC limitation[2].

Reactive power control

The reactive power control loop includes several options for controlling the reactive power and/or voltage as well as the LVRT capability function[3]. As illustrated in Figure 10, different control configurations for the reactive power can be selected: i.e. open / closed loop operation, voltage / without voltage control, power factor / reactive power control operation mode, see also Table 2. The external reference signal $X_{WTT,ref}$ can be either voltage difference or reactive power command from a wind power plant controller if available.

2 Rate-of-change (ROC) limitation will be activated, when the power plant controller will be included. All the measurements for power plant controller are performed with rate-of-change limitation.

3 LVRT is available in the proposed wind turbine model in case it is relevant for some test cases.

Selection Factor	Mode of operation in the Q control loop	
	Value: 1	**Value: 0**
M_{PF}	Power Factor	Q control
M_U	Voltage Control	Without Voltage Control
M_{OL}	Open Loop	Closed Loop

Table 3: Different modes of operation for the Q control loop and corresponding selection factors.

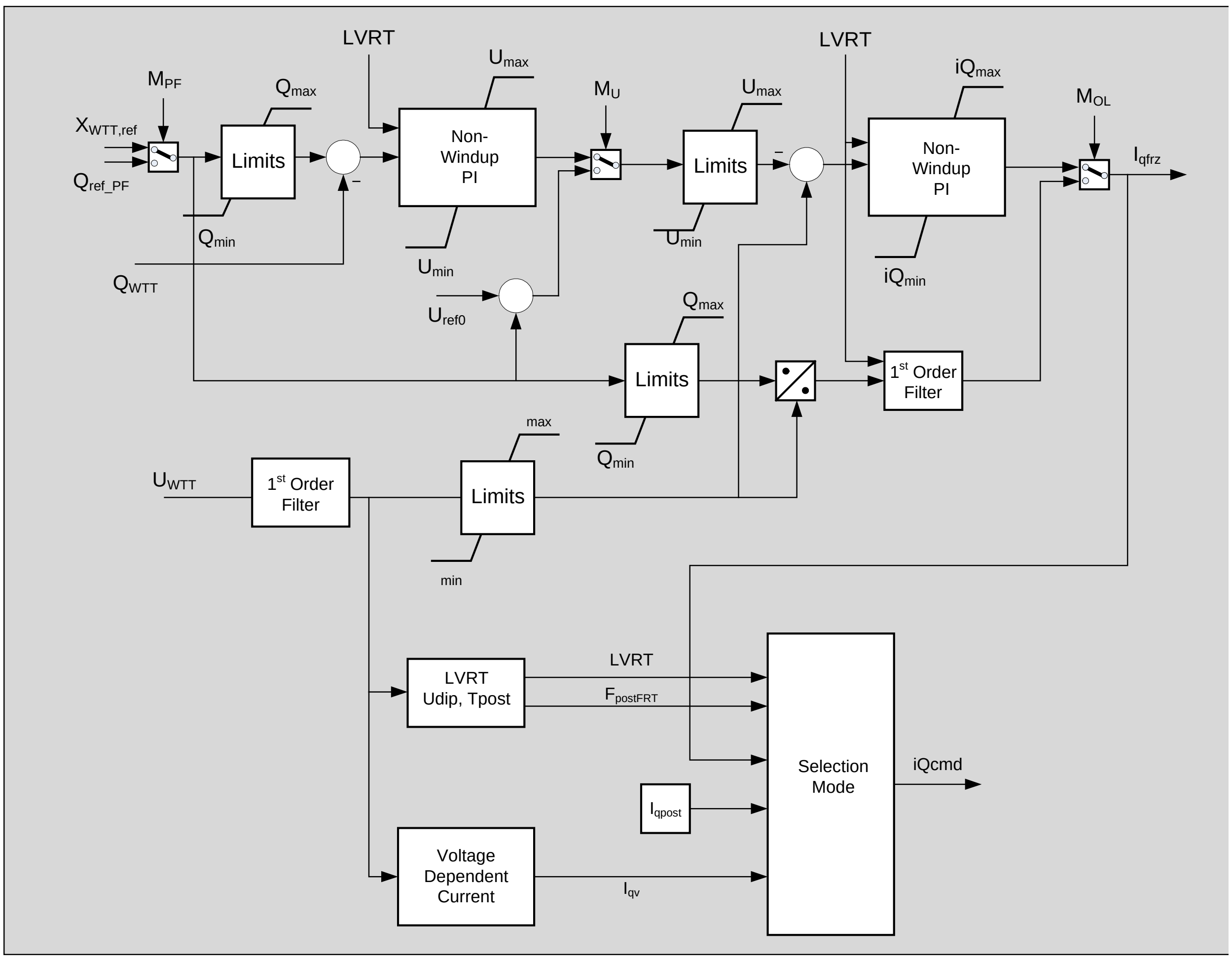

Figure 10: Reactive power control loop.

As described in IEC report [3], the reactive current control signal *iQcmd* is defined as the combination of three components, namely the voltage dependent current *Iqv*, the frozen current *Iqfrz* and the constant post fault current *Iqpost*. The industry currently offers three different options regarding the reactive current output both during normal and LVRT conditions. In this work, it has been chosen the following selection:

- During the fault the current output is defined as $i_{Qcmd}=i_{qfrz}+i_{qv}$
- After the fault, for time duration T_{post}, the current output is defined as $i_{Qcmd}=i_{qfrz}+i_{qpost}$

The LVRT detection blocks outputs the signal LVRT and the signal FpostFRT in one of the 3 following stages:

- 0: during normal operation (U_{WTT}>U_{dip}) – LVRT=0
- 1: during fault (U_{WTT}≤U_{dip}) – LVRT=1
- 2: post fault – the system stays in this stage with U_{WTT}>U_{dip} for t=T_{post}. In this stage only FpostFRT=1

The current outputs of the active and reactive power control loops are inputs to a current limiter, see Figure 12, which includes the following components:

- Limitation of the maximum continuous current during normal operation at the wind turbine terminals, i_{max}
- Limitation of the maximum current during a voltage dip at the wind turbine terminals, $i_{max,dip}$
- The maximum current ramp rate the wind turbine terminals, di_{max}
- Prioritization of active or reactive power during LVRT operation
- Voltage dependency of the active and reactive current limits provided by lookup tables $i_{P,VDL}$ and $i_{Q,VDL}$ respectively

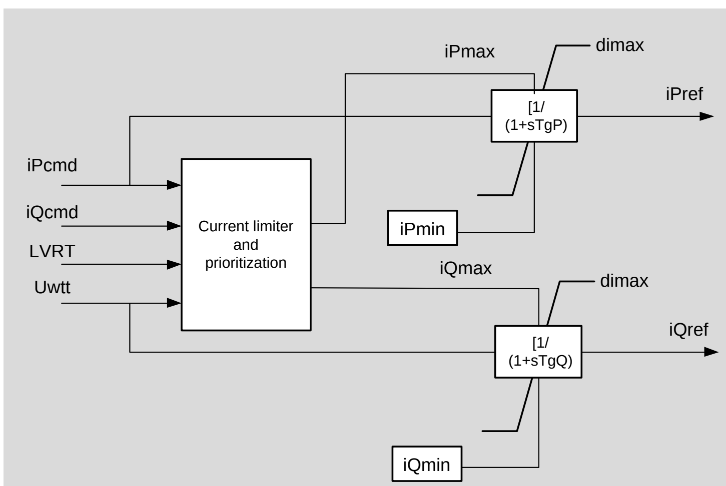

Figure 11: Active and reactive current limiter and prioritization.

It is noted here that the current limiter defines to a great extent the response of the wind turbine model especially during voltage dips and thus the limits for the currents need to be defined in a reliable and realistic way.

Available power

Figure 12 shows the implementation of the available power. The wind speed is input to the turbine power curve (P vs v) look-up table to produce the ideally available power (based on optimal pitch angle and velocity).

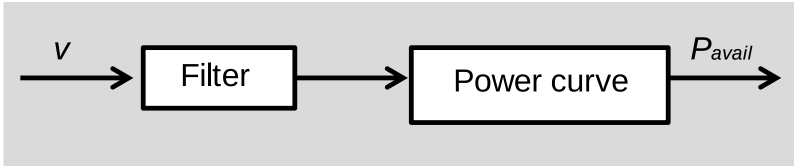

Figure 12: Available power model.

The calculation of available power at this point is based on the assumption of perfect estimation. Different methods to estimate the available power (different levels of confidence) will be investigated in the next stage of the project.

Model performance – case studies

In the following, a set of simulations are carried out in order to illustrate and evaluate the performance of the simplified Type 4 wind turbine model, proposed in this work, to account for dynamic features of interest to wind turbines primary frequency control capabilities. The network layout diagram for the simulations of the Type 4 wind turbine model is shown in Figure 13.

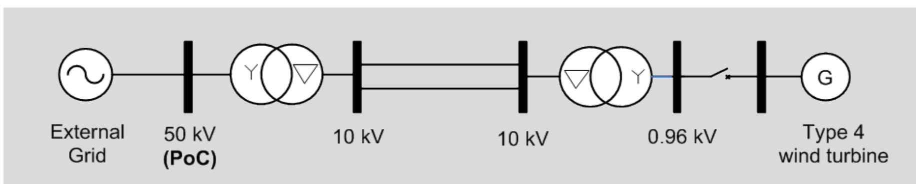

Figure 13: Layout diagram - test wind turbine.

The diagram includes a Thevenin equivalent model for the external grid, two step-up transformers, the collection cable, a circuit breaker and the wind turbine generator, which is represented by a built-in static generator model. Active and reactive power measurements are performed in wind turbine's point of connection PoC[4].

Several sets of simulations are performed and presented in the following to illustrate and analyse the model performance during:

- deterministic wind speeds
- turbulent wind speeds
- power setpoints changes
    - full load and partial operation with steps in active power setpoint
    - full load operation with steps in reactive power setpoint
    - sinusoidal active power setpoint (curtailed operation mode)
    - sinusoidal reactive power setpoint
- turbulent wind speeds and power setpoints changes
- temporary overproduction.

4 The power will be measured in the turbine terminals, instead of PoC, when wind power plant controller will be included.

Notice that the simulations presented in this report are performed based on the assumption of a perfect estimation of the available power. Different level of confidence for the available power will be considered in the next stage, when the wind power plant controller will be included.

Model performance under deterministic wind speeds

In order to evaluate the performance of the proposed model, a set of step response simulations with deterministic wind speed (no turbulence, no tower shadow) are performed in the first stage. Steps in wind of 1m/s every 20 seconds are performed. Typical quantities of the turbine system, i.e. wind speed in [m/s], pitch angle in [deg], generator speed in [rpm] and the active generator power in [MW].

Figure 14 shows the results of the simulations performed for steps in the wind speed from 12m/s up to 20m/s. Notice that the steps in the wind speed yield changes in both the pitch angle and the generator speed. The response of the pitch angle and the generator speed do not present big overshoots and oscillations. Remark also that the response of the generator speed is almost identical over the whole wind range between 12m/s and 20m/s, a fact that indicates that the gain scheduling in the speed controller is working properly. The power controller keeps the active power to 2MW with a small deviation up to 1-2%. Since the pitch mechanism reacts slowly compared to the power controller, dynamic variation in the generator speed and so in the rotational speed of the turbine rotor are allowed in order to absorb fast wind gusts and to store rotational energy in the turbine's inertia.

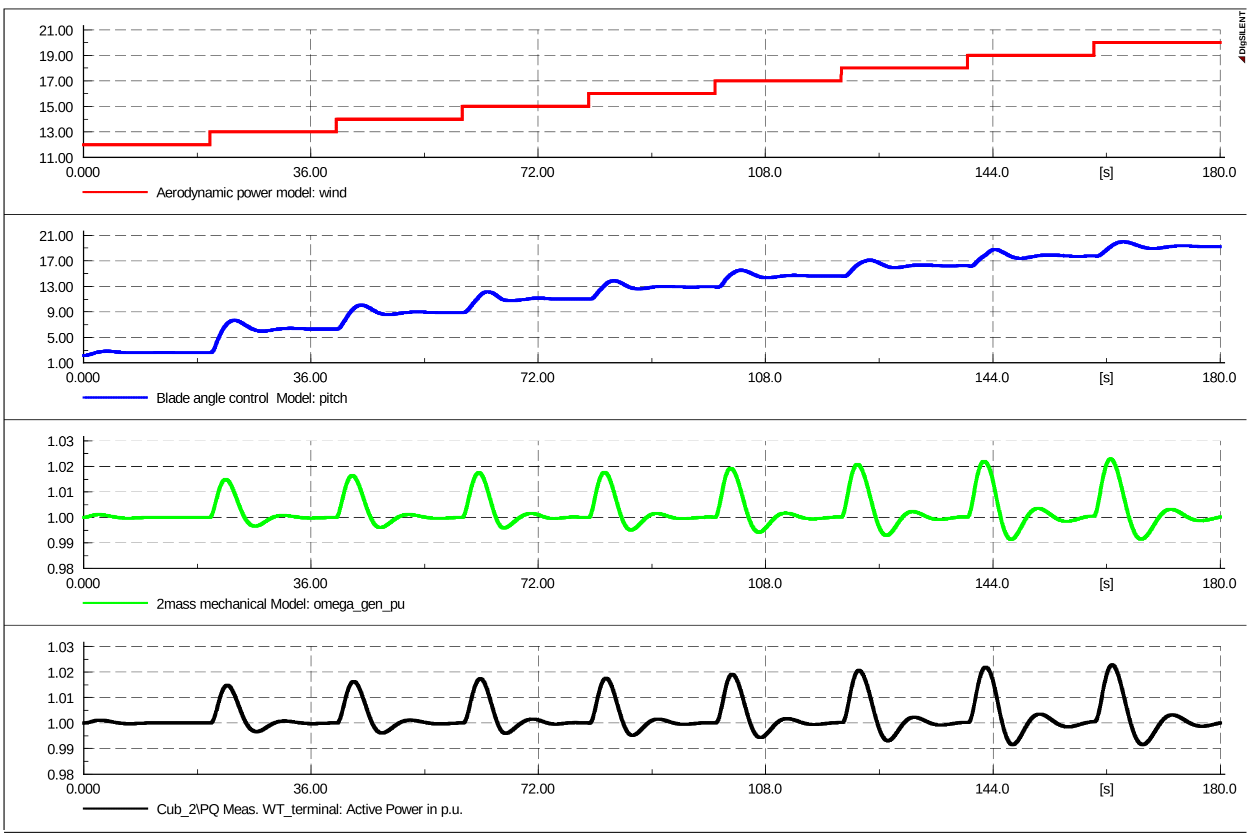

Figure 14: Wind speed [m/s], pitch angle [deg], generator speed[pu] and active power [pu] for steps in wind speed of 1m/s from 12m/s to 20m/s.

Figure 15 shows the results for steps in wind speeds from 12m/s down to 4m/s. The pitch controller is passive, keeping the pitch angle constant to the optimal value (i.e. zero for the considered wind turbine). Meanwhile, the power controller controls the active power to the active power reference signal provided by the maximum power tracking look-up table. The generator speed is continuously adapted to the wind speed, in such a way that maximum power is extracted out of wind. Notice that the response time in the steps is bigger at lower wind speeds than at higher wind speeds, caused by the high nonlinearity in the aerodynamic torque at lower wind speeds

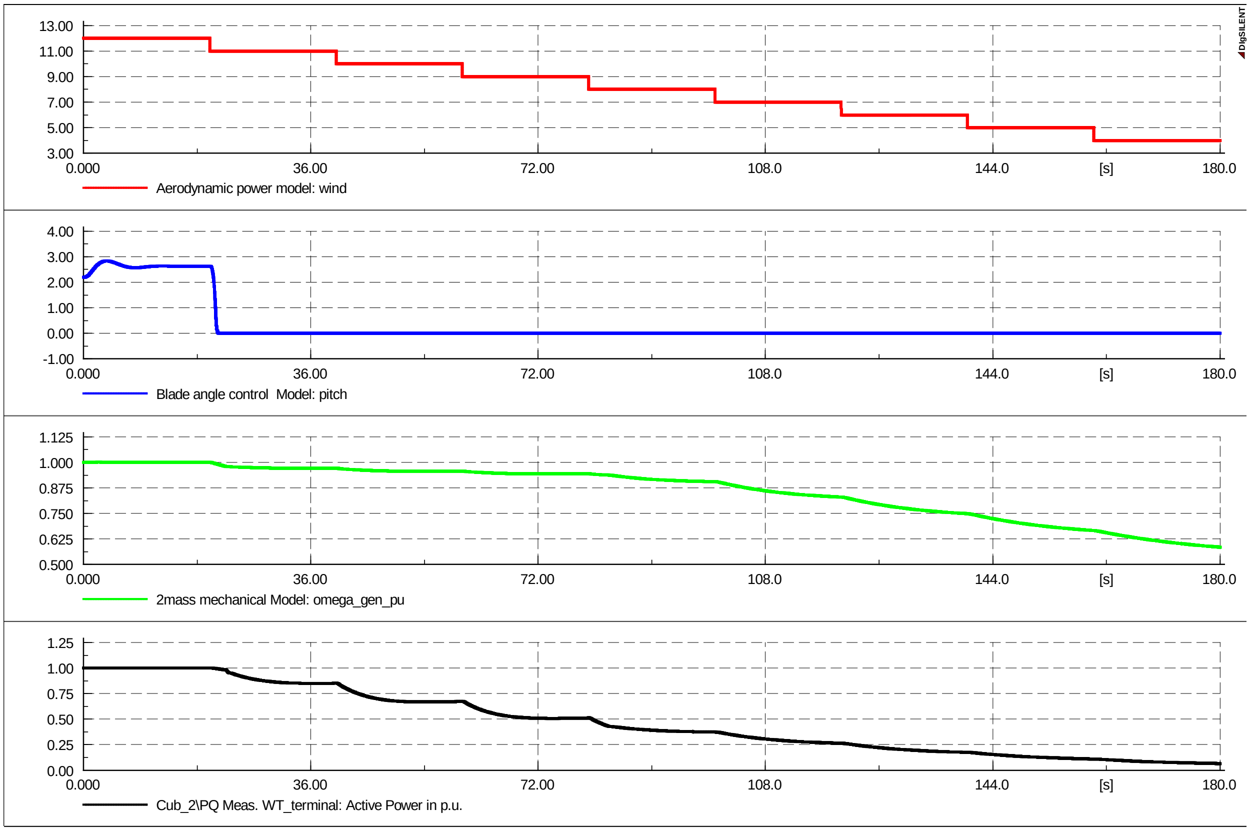

Figure 15: Wind speed [m/s], pitch angle [deg], generator speed[pu] and active power [pu] for steps in wind speed of 1m/s from 12m/s to 4m/s.

Model performance under turbulent wind speed

The performance of the wind turbine model is now illustrated for the case of stochastic wind speeds. One set of simulation with turbulent medium wind speed is considered, as shown in Figure 16. The operation point of the wind turbine due to the considered wind speed corresponds to a transition operational regime for the wind turbine, between power operation and power limitation regimes.

The generator speed is tracking the slow variation in the wind speed. As expected for lower wind speeds than 11.8 m/s, the pitch angle is passive, being kept constant to its optimal value (i.e. zero for the considered wind turbine). The active power delivered to the grid does reflect the variation in the wind speed. Notice that the fast oscillations in the wind speed are completely filtered out from the electrical power.

For the considered wind speed time series the turbine operates partly at rated conditions and partly at partial load. As soon as rated wind speed is exceeded, the pitch angle increases and limits the speed. The power is kept to the rated power as long as the energy in the wind permits that.

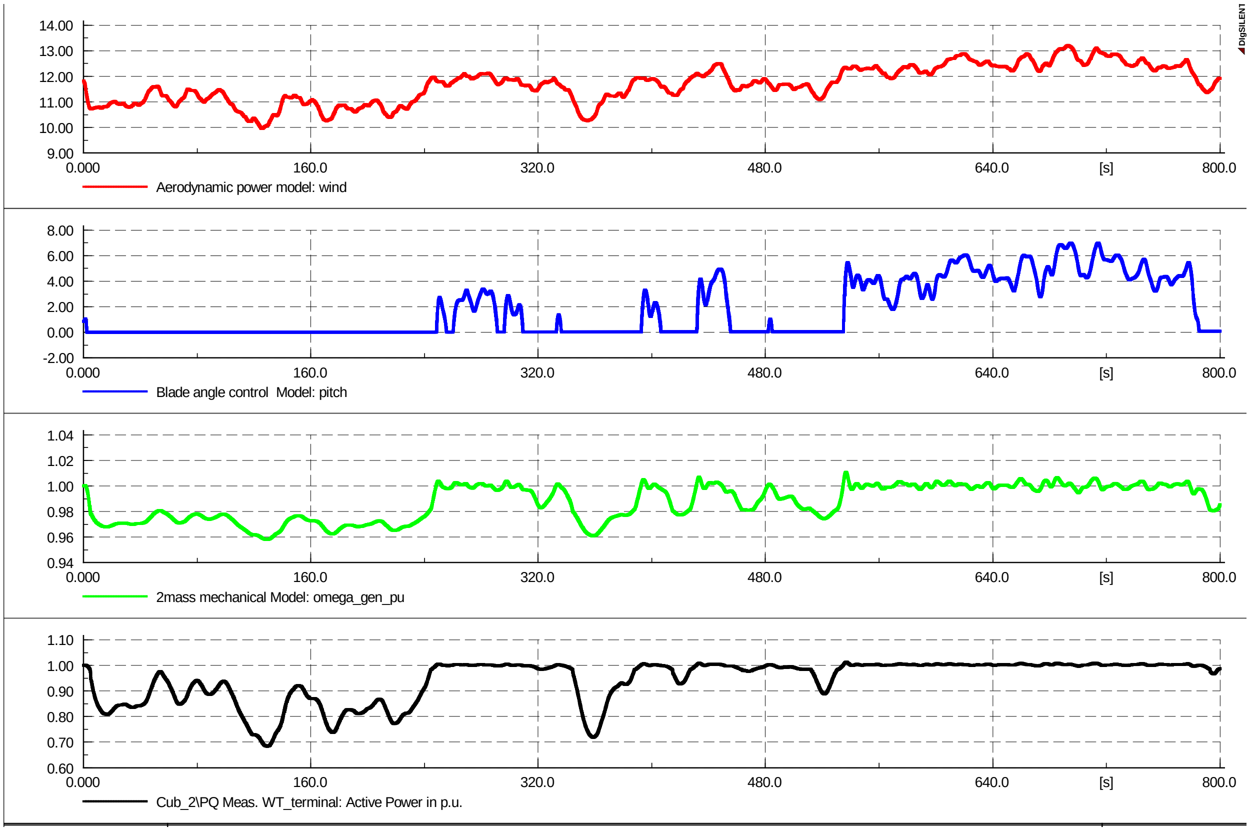

Figure 16: Turbulent medium wind speed. Wind speed [m/s], pitch angle [deg], generator speed[pu] and active power [pu].

Model performance under power setpoints changes

In order to evaluate the performance of the proposed wind turbine model to different setpoints for the active and reactive power, a set of step response simulations first with deterministic wind speed and then with stochastic wind speed are performed in the following.

Wind turbine full load operation with steps in active power setpoint

Figure 17shows the performance of the wind turbine model during steps in the active power setpoint of the wind turbine.

Figure 17 illustrates the pitch angle, the rotor and the generator speed, the shaft torque as well as the active power production and the active power setpoint in case of a wind speed of 13 m/s (1.1pu wind speed), which corresponds to full load operation. Steps in power setpoint of 0.125 pu every 60 seconds are performed. The power setpoint is first stepped down from 1pu to 0.125pu and then, after 480 sec, it is stepped back to 1pu. Notice that Figure 17contains two graph zones: the first shows the whole simulation sequence, while the second provides detailed views (zooms) on the wind turbine response when a change in the active power setpoint is demanded. Both a step down (power curtailment) and a step up in the active power setpoint are illustrated in the zoom.

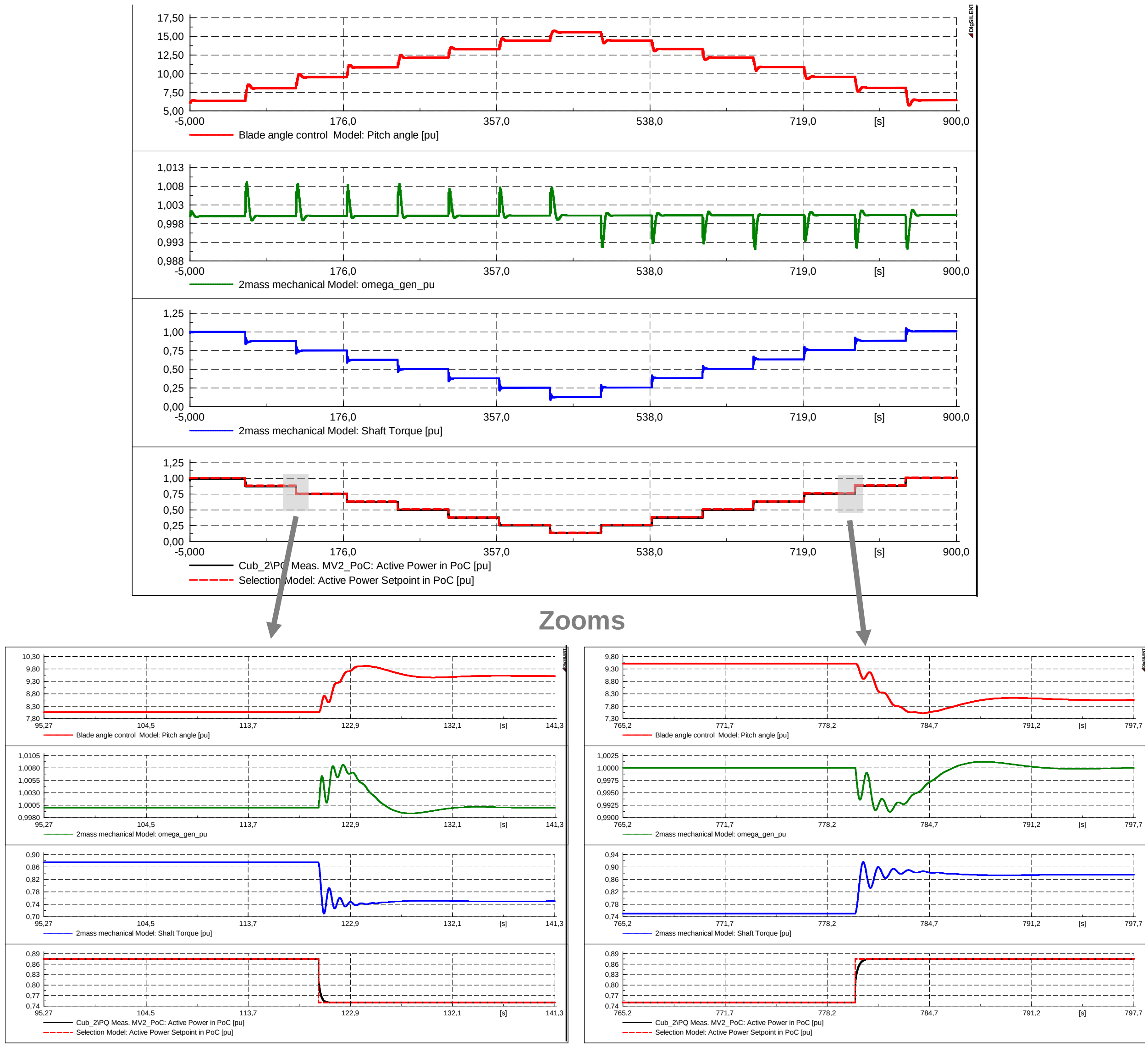

Figure 17: Steps in the active power reference Pref for a 13m/s constant wind speed (1.1pu). Signals: Pitch angle [deg], generator speed [pu], rotor speed [pu], shaft torque [pu] and active power [pu].

Notice that, as expected, the steps in active power lead to changes in the steady state value of the pitch angle. A reduction of the power production implies an increased pitch angle. The generator speed keeps its steady state value, while it presents small transients due to the steps in power. The zoom also illustrates the dynamics of the generator. These dynamics are also reflected, as expected, in the shaft torque. The torsional oscillations, accounted because of using the 2-mass model for the mechanical model, are visible in the generator speed as well as in the shaft torque. The frequency of these oscillations depends on the parameters of the mechanical system. The shaft torque decreases while the active power decreases. Notice that the shaft torque oscillations are damped within 3 sec and that the drive train is not mechanical stressed as the shaft torque oscillations do not cross through zero.

Figure 17 also proves correct dynamic of the active power, which follows the changing power setpoints. The proposed wind turbine model is able to account for the dynamic features expected from the model during steps in the active power demand.

Wind turbine partial load operation with steps in active power setpoints

Figure 18 shows the results of the steps in active power setpoint when the turbine is operating at 8m/s wind speed (0.68pu). Wind speed steps of 1m/s every 20 seconds down to 8 m/s are first performed. The reason for starting wind turbine in full operation is because the model can be initialised only in full load operation.

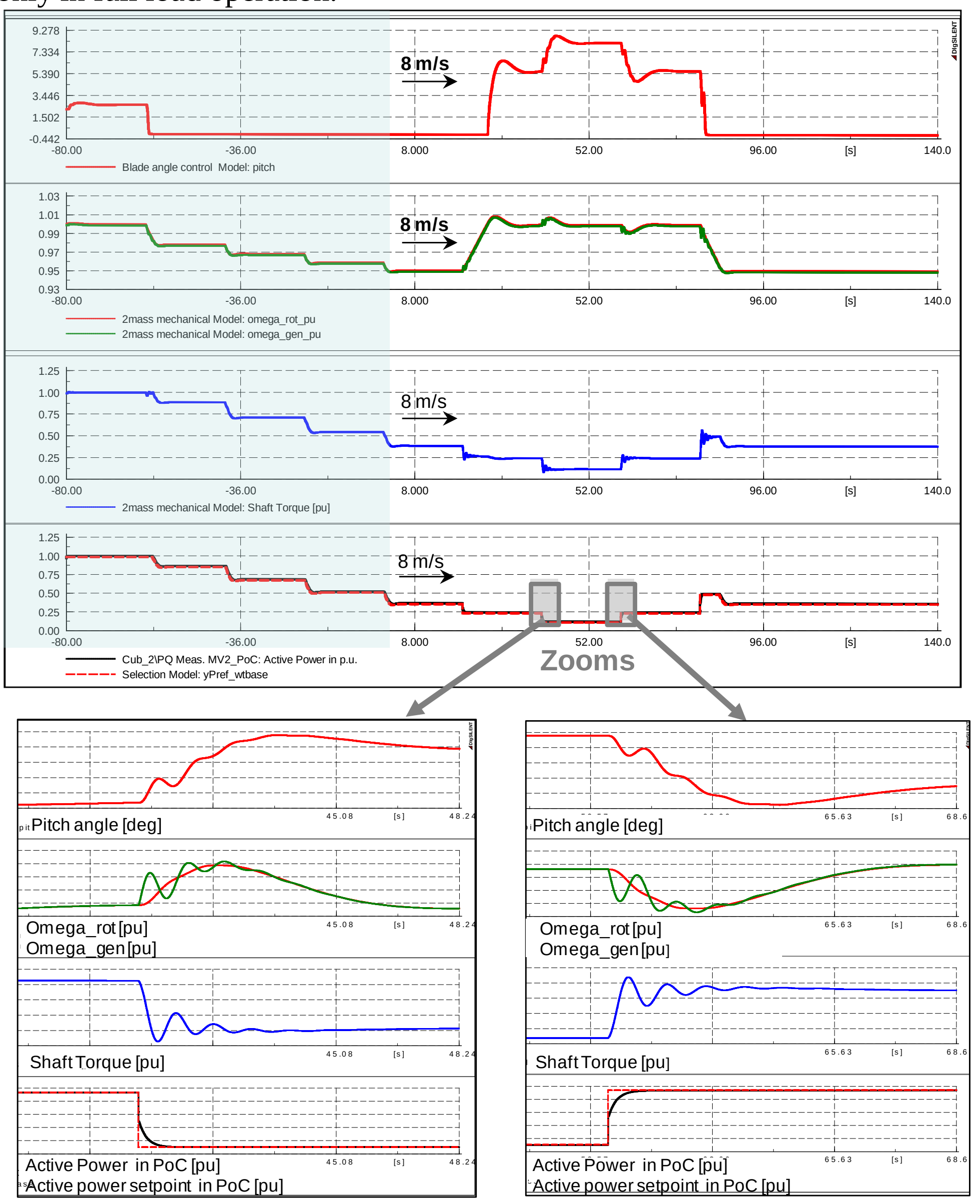

Figure 18: Steps in the active power setpoint for a 8m/s deterministic wind speed (0.68pu). Signals: wind speed [m/s], pitch angle [deg], generator speed[pu], rotor speed [pu], shaft torque [pu] and active power [pu].

When the turbines operation for 8m/s is in steady state, steps in active power setpoint of 0.1 pu every 60 seconds are performed (first down and then up). By derating the turbine the pitch angle and the generator speed are as expected increased. The simulations indicate a good performance of the power controller.

Figure 18 contains also two graph zones: the first shows the whole simulation sequence, while the second provides detailed views (zooms) on the wind turbine response when a change in the active power setpoint is demanded. Both a step down (from 0.2pu to 0.1pu) and a step up (from 0.1pu to 0.2pu) in the active power setpoint are illustrated in the zoom.

Similar to Figure 17, Figure 18 proves correct dynamic of the active power, which follows the changing power setpoints during a partial load operation.

Wind turbine full load operation with steps in reactive power setpoint

Figure 19 shows the performance of the wind turbine model during steps in reactive power setpoint. Figure 19 illustrates the voltage in wind turbine's point of connection PoC, the generator speed, the active power and the reactive power in PoC, with their setpoints, respectively, in case of a wind speed of 13m/s (1.1pu).

Steps in reactive power setpoint of 0.1 pu every 20 seconds are performed. Notice that the active and reactive powers are controlled independently. The steps in reactive power do not affect the active power, neither the generator speed.

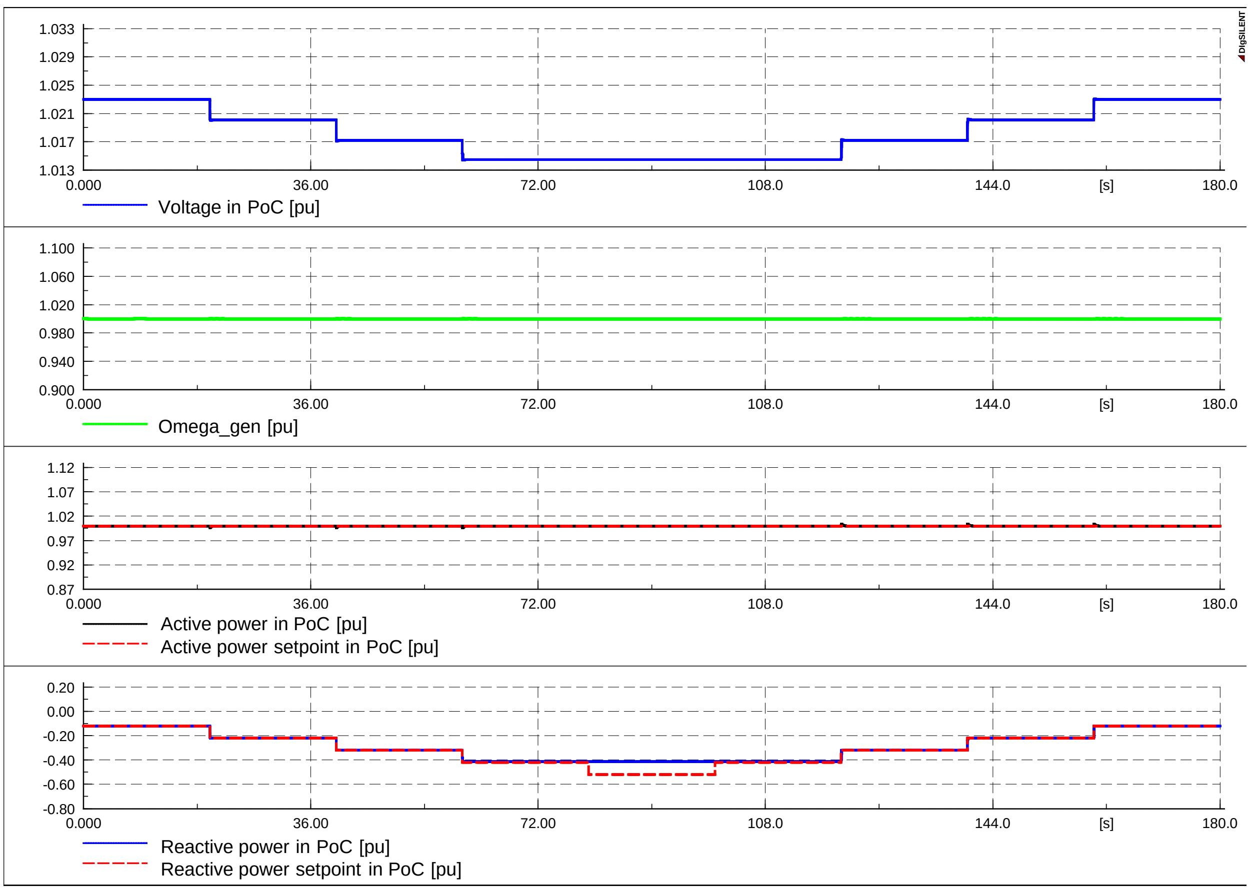

Figure 19: Steps in the reactive power setpoint. Signals: voltage in PoC [pu], generator speed [pu], active power [pu] and reactive power [pu].

The reactive power follows very well its reference as long as the controller does not reach its maximum or minimum limit. Steps in the reactive power production of the wind turbine yield to changes in the voltage in PoC, as there is no voltage controller activated in the wind turbine model.

Wind turbine operation during sinusoidal active power setpoint (derating mode)

The analysis of the performance of the wind turbine model is further supported by performing dynamic simulations of the turbine in a curtailed operation and with a sinusoidal active power setpoint. After the wind turbine is derated with 0.1 pu for a period of 30 seconds, a sinusoidal signal of 0.1pu magnitude and 0.1Hz is added to the active power setpoint. Figure 20 illustrates the simulation results for a deterministic wind speed of 8m/s (0.68pu) (partial load operation of the turbine), while Figure 21 illustrates the simulation results for a fixed wind speed of 13m/s (1.1pu) (full load operation of the turbine). The simulations indicate a good performance of the model and controller – the wind turbine follows very well the active power reference. As illustrated in Figure 9, the power reference is defined by the minimum between the optimal power and the power setpoint coming from the wind farm control. This is reflected in
Figure 21, where the active power reference has a sinusoidal form as long as the power setpoint coming from the wind farm control is smaller than the optimal power.

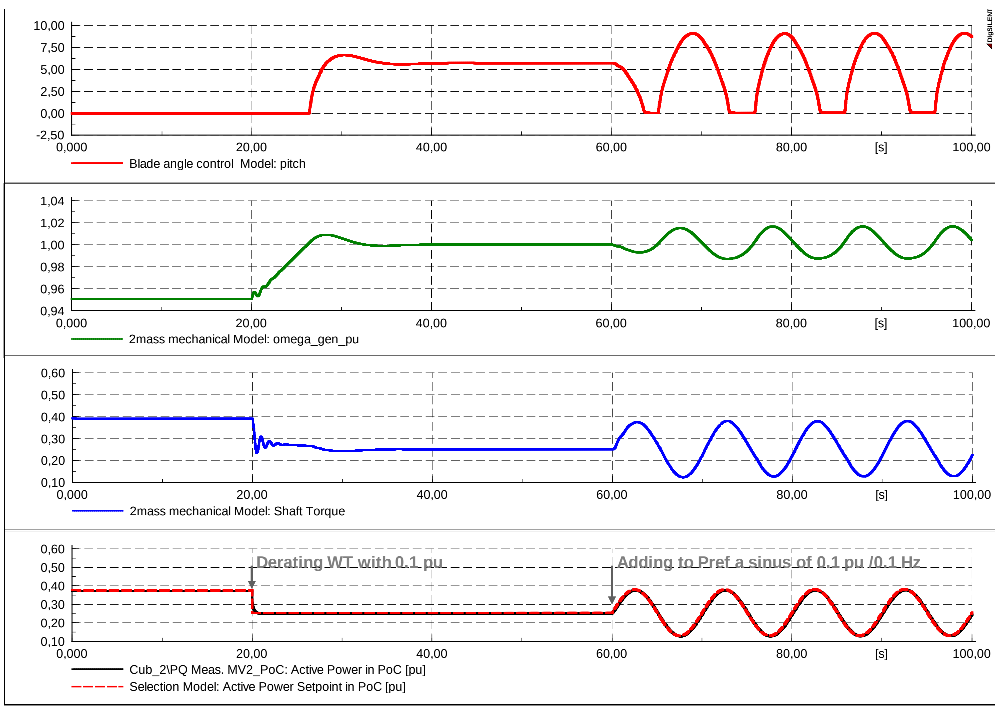

Figure 20: Derating wind turbine with 0.1pu and add sinus with 0.1 magnitude and 0.1Hz in top of the active power setpoint in partial load (constant wind speed of 8m/s (0.68pu)),

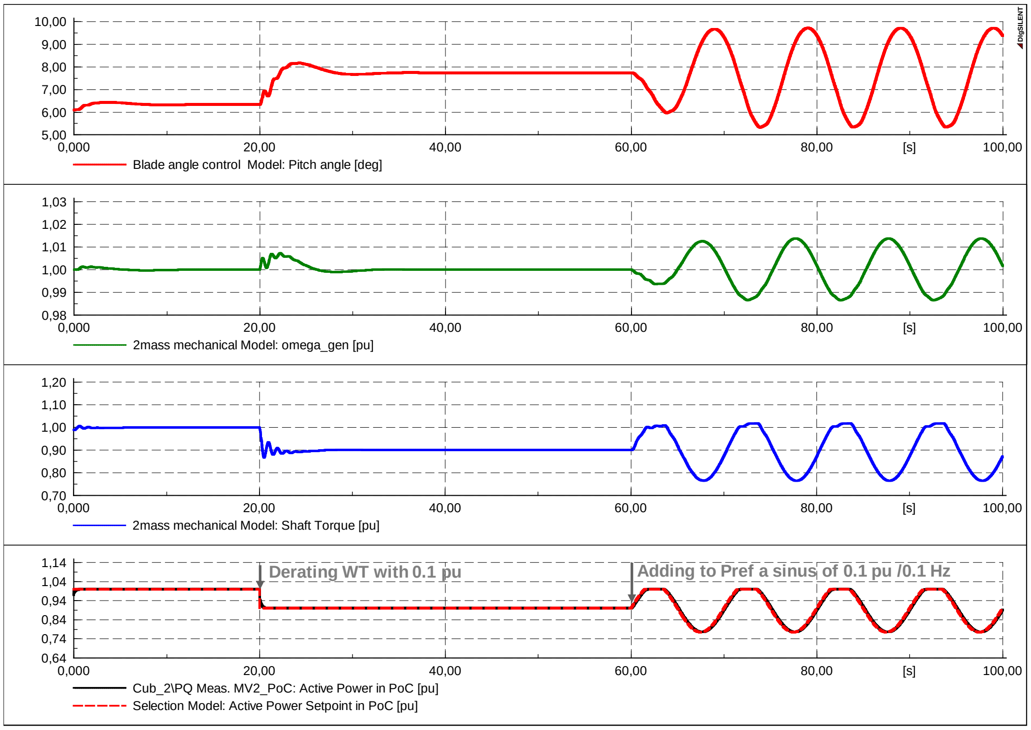

Figure 21: Derating wind turbine with 0.1pu and add sinus with 0.1 magnitude and 0.1Hz in top of the active power setpoint in full load (constant wind speed of 13m/s (1.1pu)).

Wind turbine operation during sinusoidal reactive power setpoint

Figure 22 show**s** the results of the simulations of the turbine in full load operation (wind speed 13m/s (1.1pu)) with a sinusoidal reactive power setpoint. A stepping down in the reactive power reference is initially applied in order to check the performance of the model in the operation range close to the lower reactive power limit set in the controller. The reactive power follows the sinusoidal reference accurately as long as the limit is reached, in which case the reactive power is kept constant.

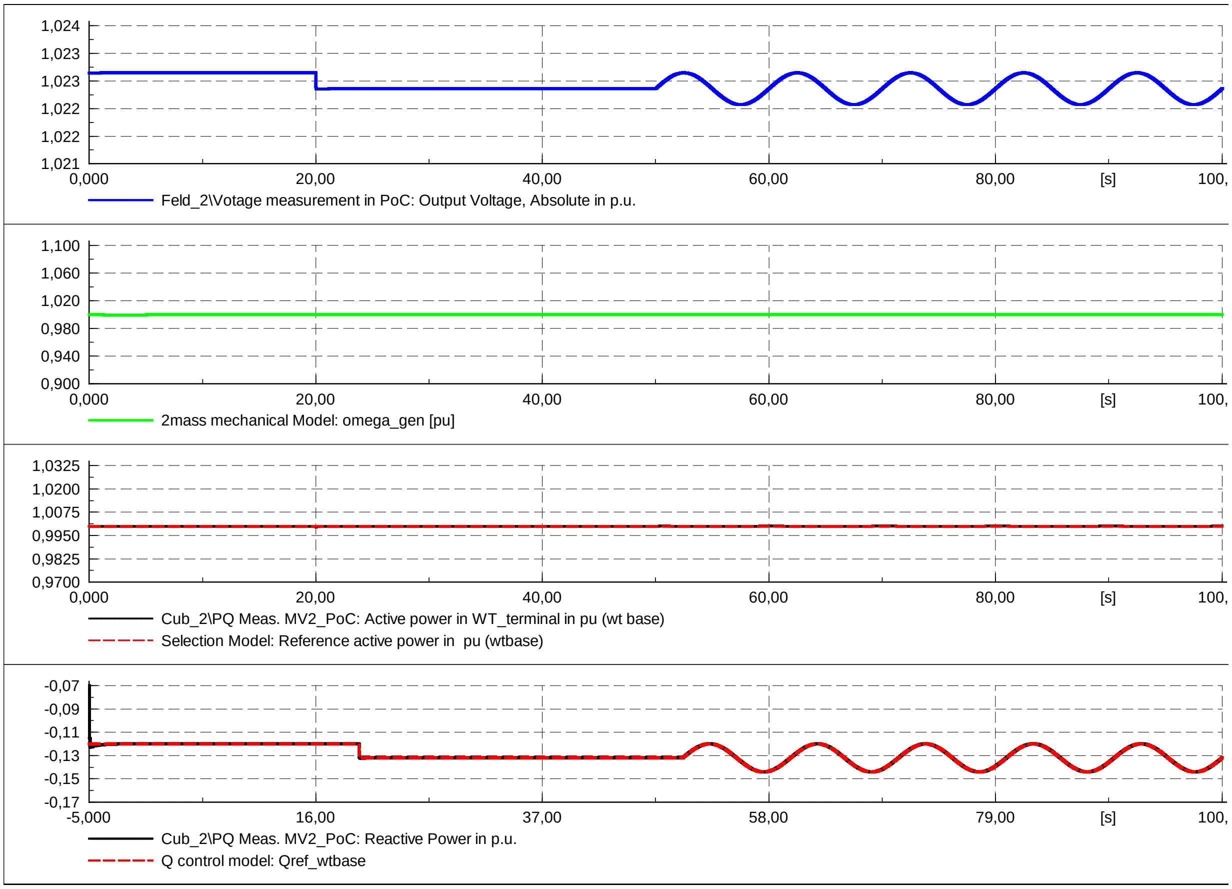

Figure 22: Sinusoidal reactive power reference Signals: Signals: voltage in PoC [pu], generator speed [pu], active power [pu] and reactive power [pu].

The reactive power follows very well its reference as long as the controller does not reach its maximum or minimum limit. Notice that a sinusoidal reactive power setpoint yields also to a sinusoidal voltage in PoC, as there is no voltage controller activated in the wind turbine model.

Model performance under turbulent wind speed and power setpoint changes

Figure 23 and Figure 24 present the simulation results of the model for turbulent wind speed and steps in the active and reactive power setpoints. The capability to control independently the active and reactive power production to the grid is also illustrated. The same wind speed time series, illustrated in Figure 16, is used now for analysing the performance and power grid support capabilities of the presented wind turbine model both during turbulent wind speed and power setpoint changes.

In order to illustrate the performance of the wind turbine's control system, several steps in active power setpoint are performed, as illustrated in Figure 23, and in reactive power setpoint, as illustrated in Figure 24, respectively. The following sequence is assumed. During the first 260 s, the wind turbine has to produce maximum active power. In this case the pitch angle is set to zero as the wind turbine works in the power optimization regime, while the speed tracks the slow variations in the wind speed. The power reflects the optimal power according to the generator speed and the MPPT look-up table. In the time period between 260 and 320s, the active power reference is first stepped down to 0.9pu, then after 60s down to 0.6pu and then it is stepped back again to 0.6pu and 0.9pu, respectively and then finally back to maximum power demand at the time 560s. Notice that, a reduction of the power production implies as expected an increased pitch angle and generator speed.

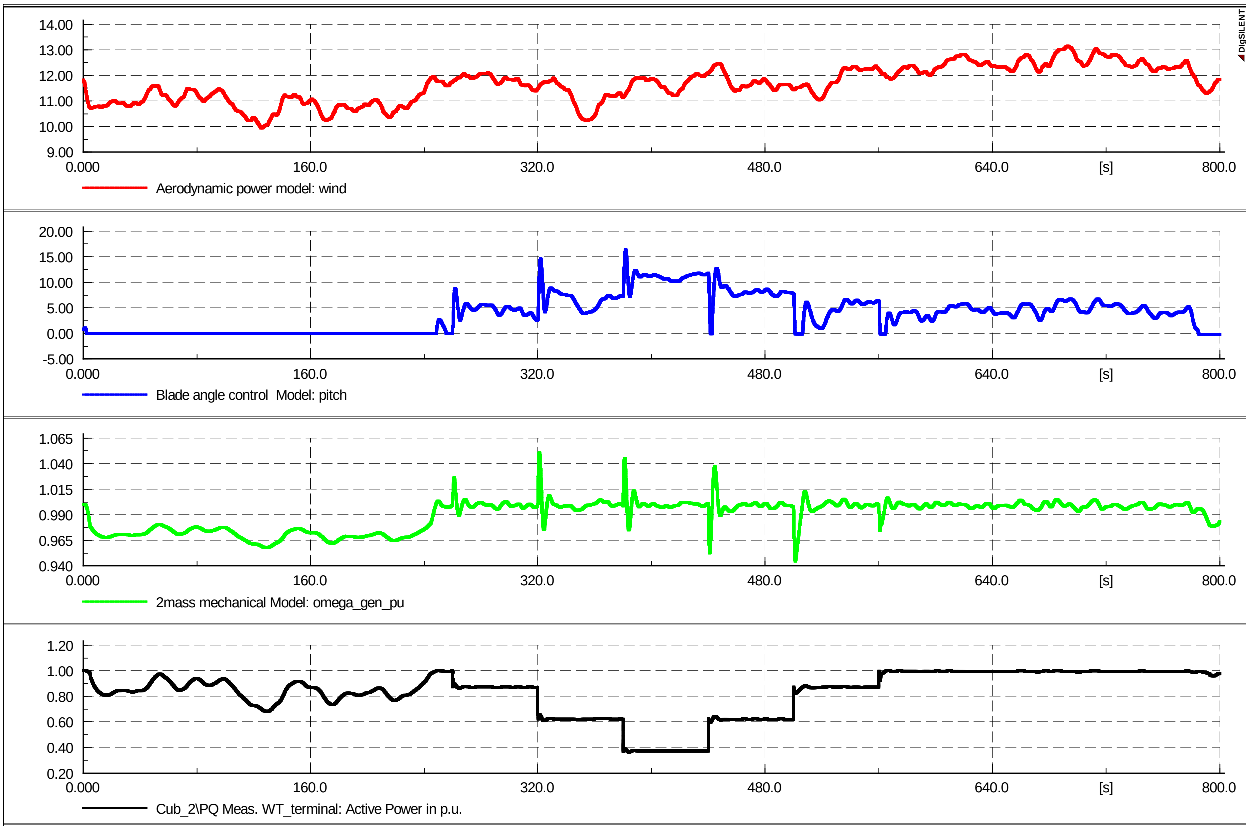

Figure 23: Turbulent wind speed and steps in active power setpoint. Signals: Wind speed [m/s], pitch angle [deg], generator speed[pu] and active power [pu].

In Figure 24, different steps in reactive power are shown, the wind turbine being demanded to absorb or to produce reactive power to the grid - a request which is also well accomplished. Notice that the generated active power is not altered by the step in the reactive power demand, its variations being only due to the turbulent wind.

The simulation results indicate good performance of the presented simplified wind turbine model. The specified setpoints both for the active and reactive power are achieved properly. This illustrates a good performance of the proposed simplified model for Type 4 wind turbine, reflecting the power support capabilities of Type 4 wind turbines, namely that they can control their active and reactive power to imposed setpoint values, as conventional power plants do.

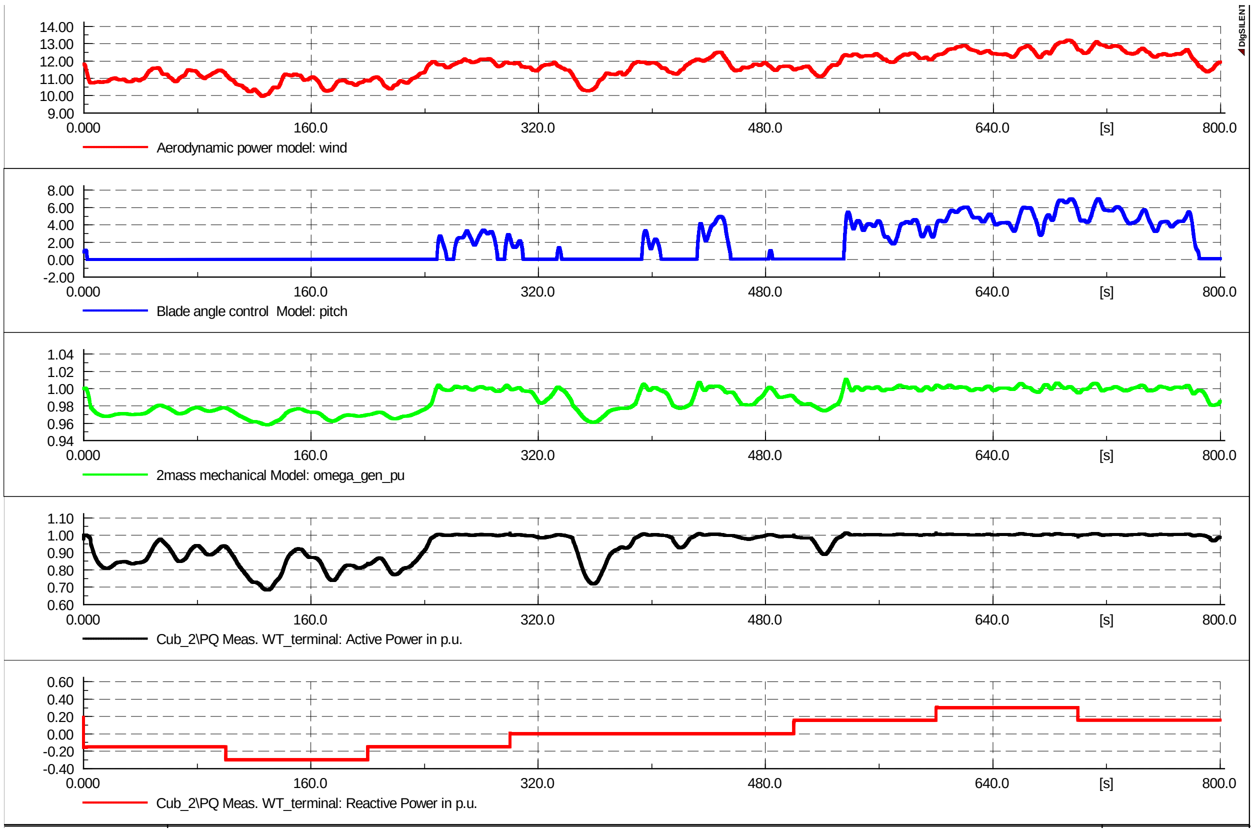

Figure 24: Turbulent wind speed and steps in reactive power setpoint. Signals: wind speed [m/s], pitch

Model performance during temporary overproduction

In order to evaluate how the proposed wind turbine model handles any request in boosting power on top of the available power, a set of simulations are performed and illustrated in the following for different operational modes of the wind turbine (partial and load), different overproduction levels (5%, 10% and 20%) and overproduction periods (2sec and 10 sec).

Temporary overproduction in partial load operation

Figure 25 illustrates wind turbine response during temporary overproduction for wind speed 6m/s, i.e. 0.51pu, namely for a low wind speed, where optimum rotor speed is lower than 0.9 pu. Overproduction duration of 2 sec is considered. The illustrated signals are the pitch angle, the generator speed, the active power and the active power setpoint, aerodynamic power, available power and the shaft torque. Notice that, for this case the deviation in the speed during overproduction is not significant and therefore there is no drop in the aerodynamic power. The higher the overproduction step, the longer the recovery time and the higher the shaft torque are.

Figure 26, Figure 27 and Figure 28 illustrate the results for operation at 8 m/s (0.68pu) wind speed and demanded overproduction duration time of 2 sec, 10 sec and 30 sec, respectively. Notice that for wind speeds lower than the rated wind speeds and where the optimal speed is higher than 0.9pu, the deviation in the speed yields drops in the aerodynamic power. This results in the reduction of the active power output after the overloading for a period of time, referred to as recovery period.

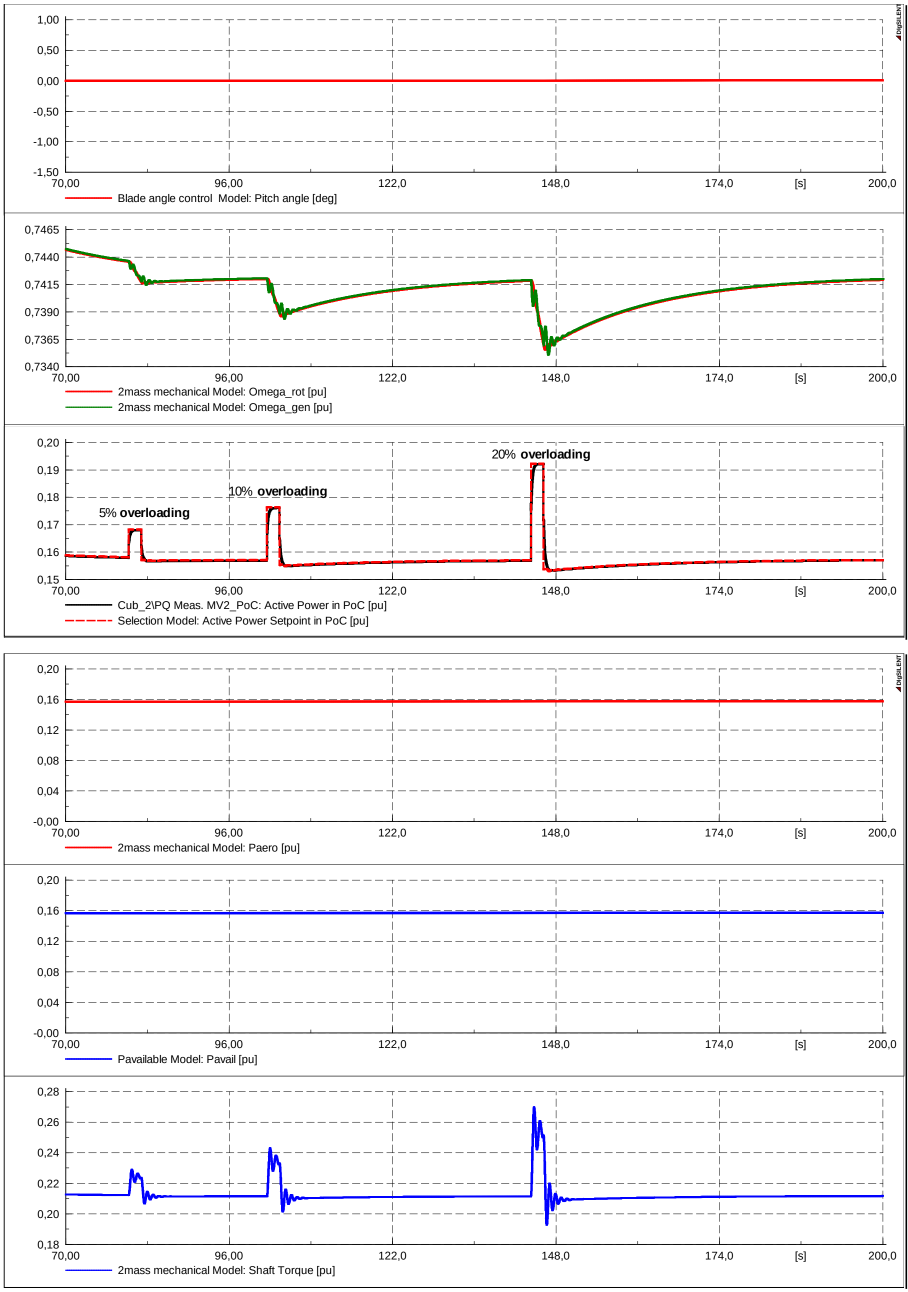

Figure 25: Overproduction with 5%, 10%, 20% respectively, during 2 sec at 6m/s (0.51pu) deterministic wind speed.

In this range of wind speeds lower than the rated wind speed, the pitch remains constant at the optimal value of 0 deg and the rotor speed decelerates during the overproduction. The higher the overloading step the longer the recovery period is. Notice that the generator speed decreases during overproduction and increases when the overproduction is stopped.

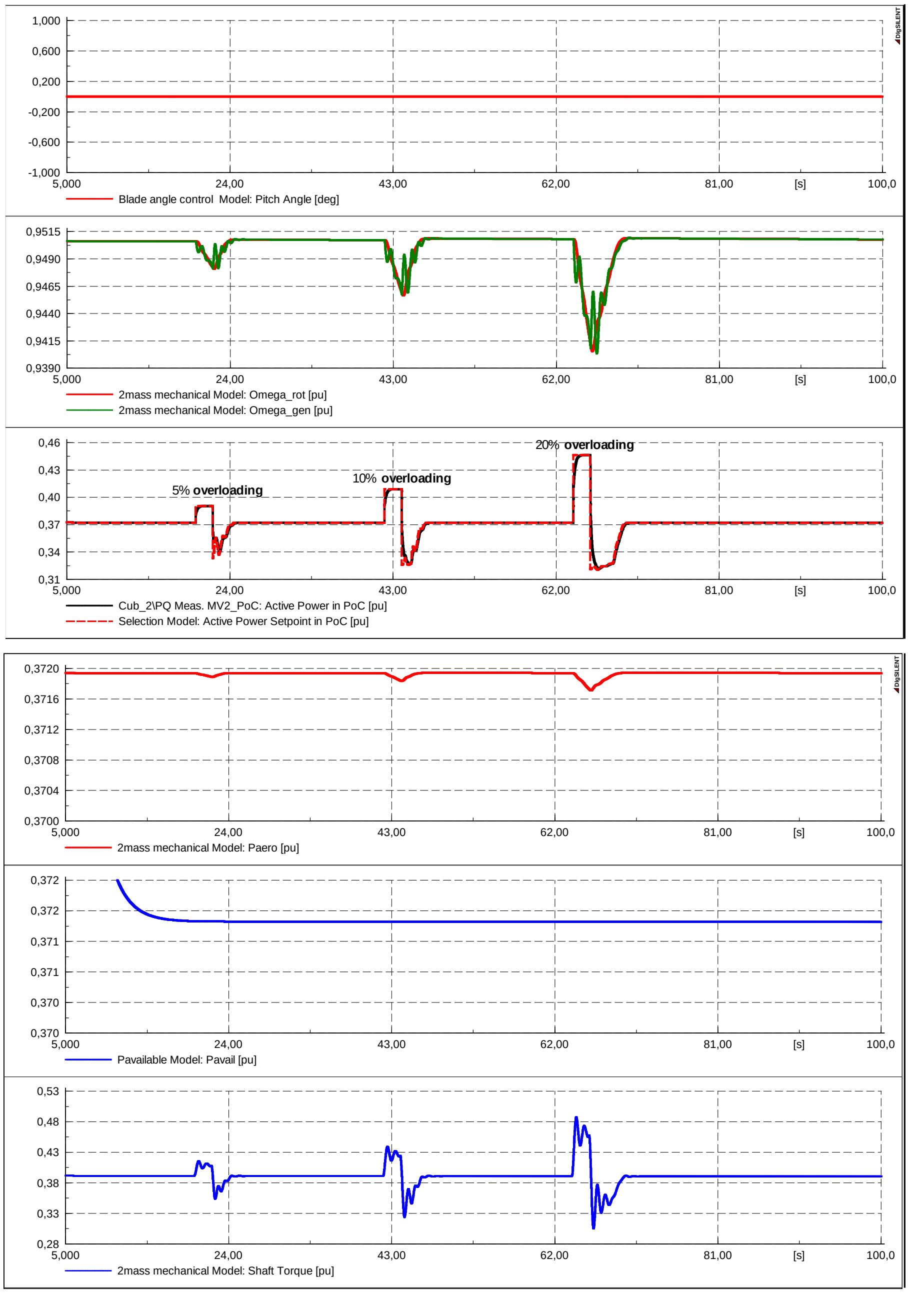

Figure 26: Overproduction with 5%, 10%, 20% respectively, during 2 sec at 8m/s (0.68pu) deterministic wind speed.

As expected, the longer the overproduction period, the deeper the decrease in the generator speed and the longer recovery time are. Notice also that, the shaft torque increases slightly the longer the overproduction period is.

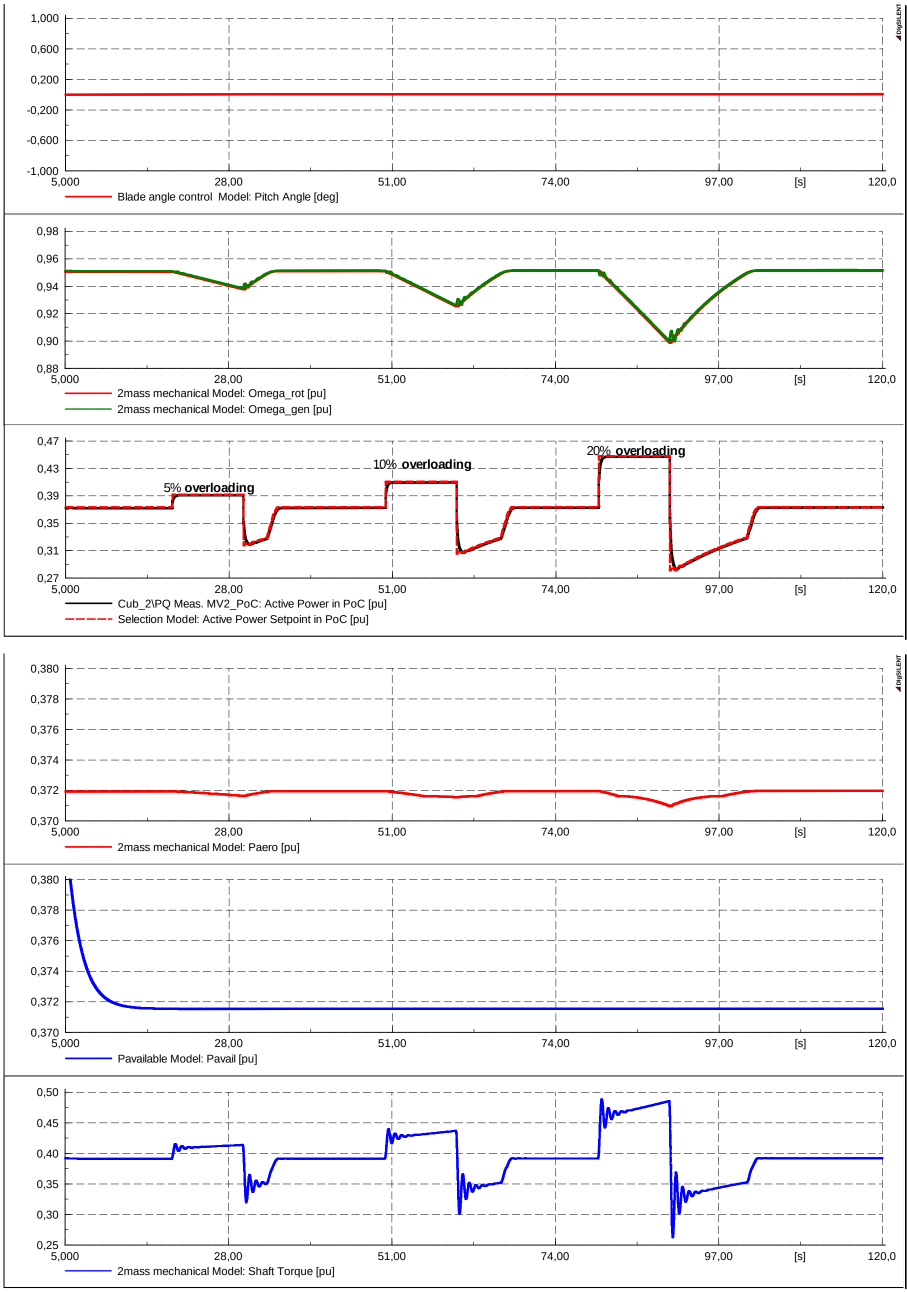

Figure 27: Overproduction with 5%, 10%, 20% respectively, during 10 sec at 8m/s (0.68pu) deterministic wind speed.

Notice that, by increasing the overproduction period, there is a risk that the generator speed decelerates beyond the speed limit of the MPPT curve[5] and the wind turbine stops. In the moment that the generator speed reaches this limit, the "selection mode" block in Figure 3 should disregard the overproduction demand from the wind farm controller and provide active power setpoint to the wind turbine only based on MPPT table.

5 Minimum value and maximum values for generator speed are 0.5pu and 1pu, respectively. See appendix .

It is also worth noticing in Figure 27 and Figure 28 that the drop of electrical power of the wind turbine is much larger than the drop in the aerodynamic power P_{aero} of the wind turbine, e.g. 0.15 pu difference in Figure 28. This indicates the need of a dedicated recovery control to avoid such a large power drop, for no curtailment operation. However, it is expected that when the rate-of-change (ROC) will be activated, the drop in power will not be so large.

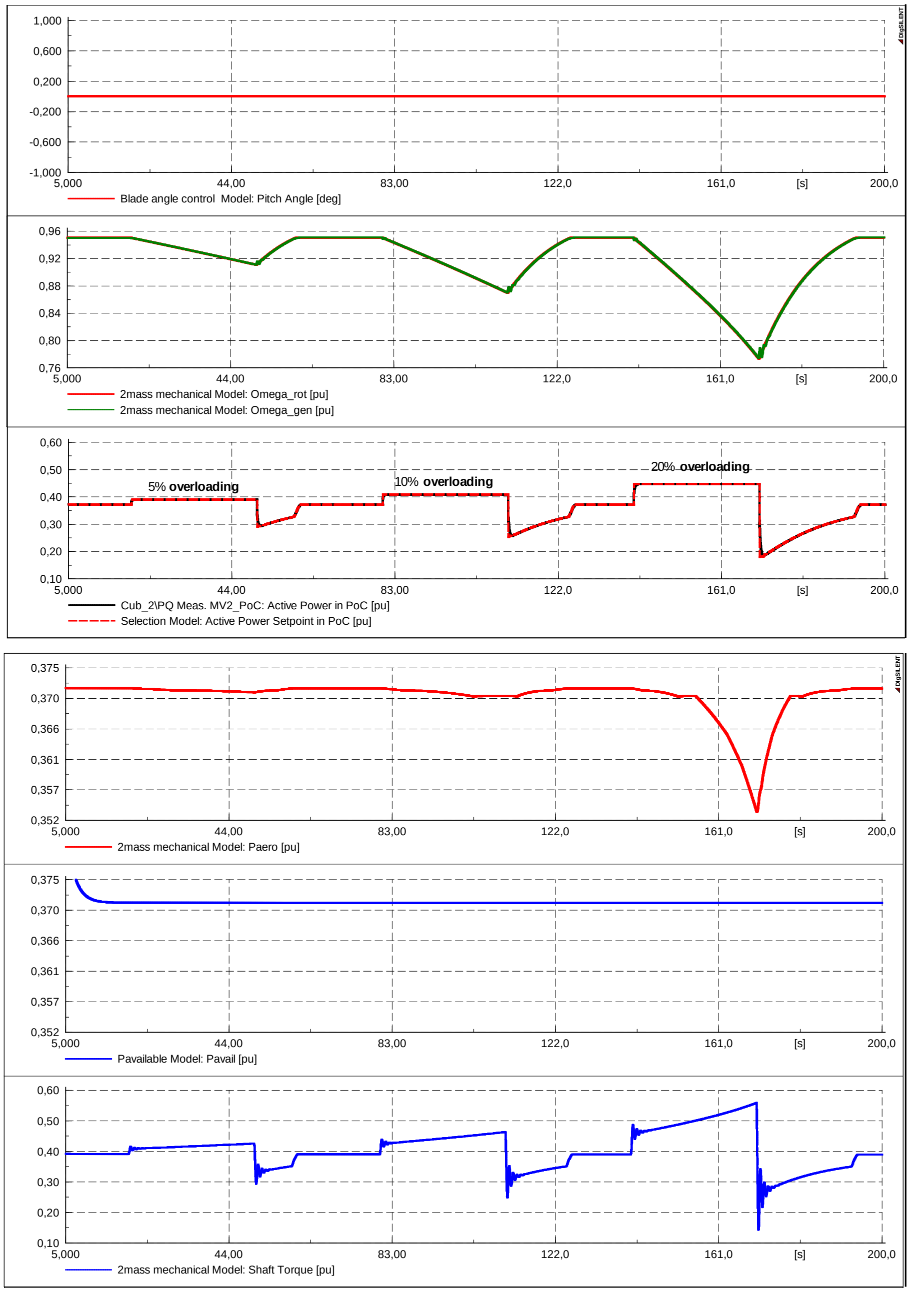

Figure 28: Overproduction with 5%, 10%, 20% respectively, during 30 sec at 8m/s (0.68pu) deterministic wind speed.

Wind turbine's operation near to the rated wind speed during overproduction is illustrated in Figure 29, Figure 30, Figure 31 and Figure 32 for 11.5m/s (0.97pu) wind speed and overproduction duration time of 2 sec and 10 sec, respectively. Both figures contain two graph zones: the first shows the whole simulation sequence, while the second provides a zoom of the wind turbine response. The simulation results are similar as those described for Figure 26. However, deviations in the speed and power are larger during the recovery period for this critical wind speed.

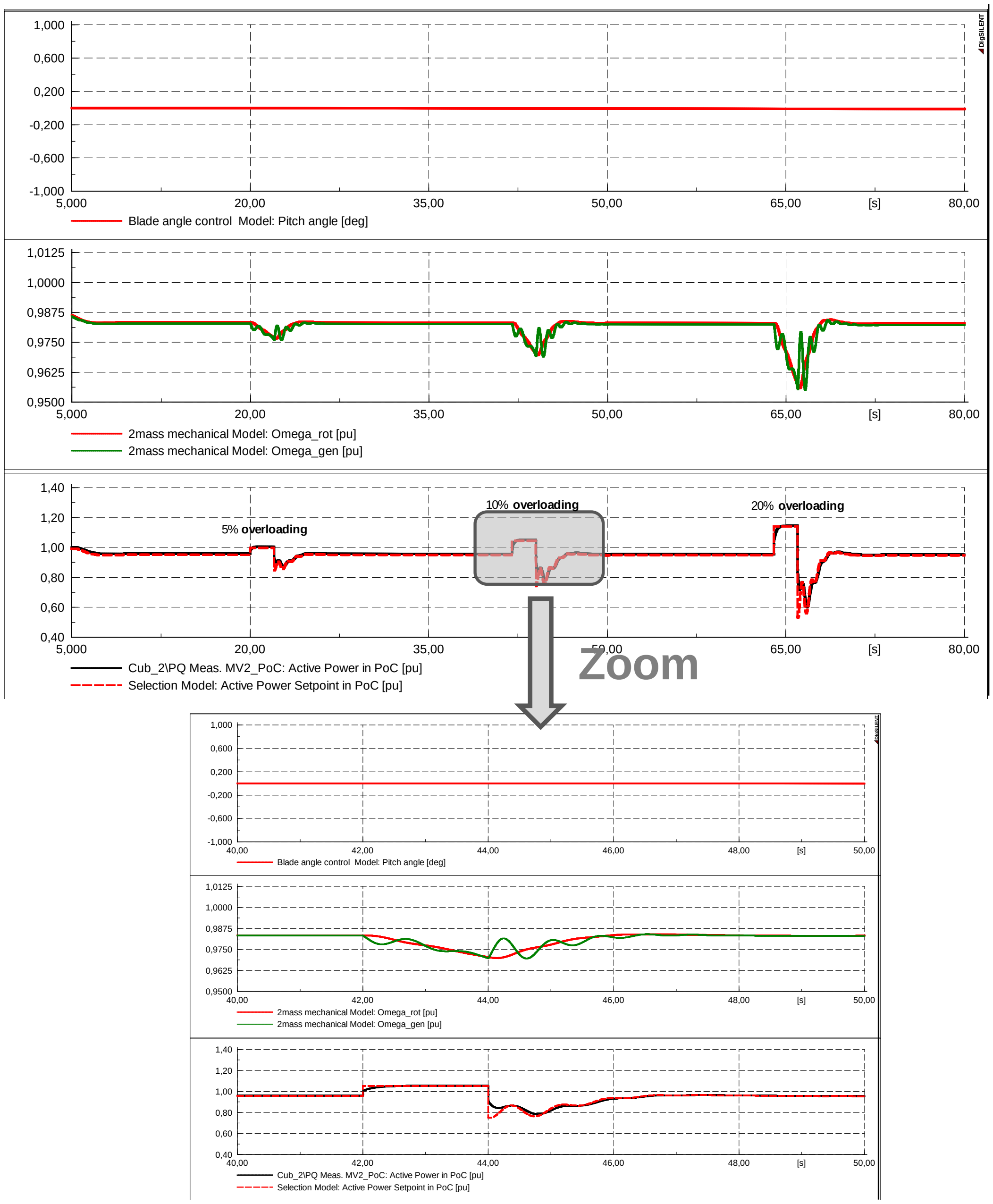

Figure 29: Overproduction with 5%, 10%, 20% respectively, during 2 sec at 11.5m/s (0.97pu) deterministic wind speed: pitch angle, generator and rotor speed, active power and its setpoint.

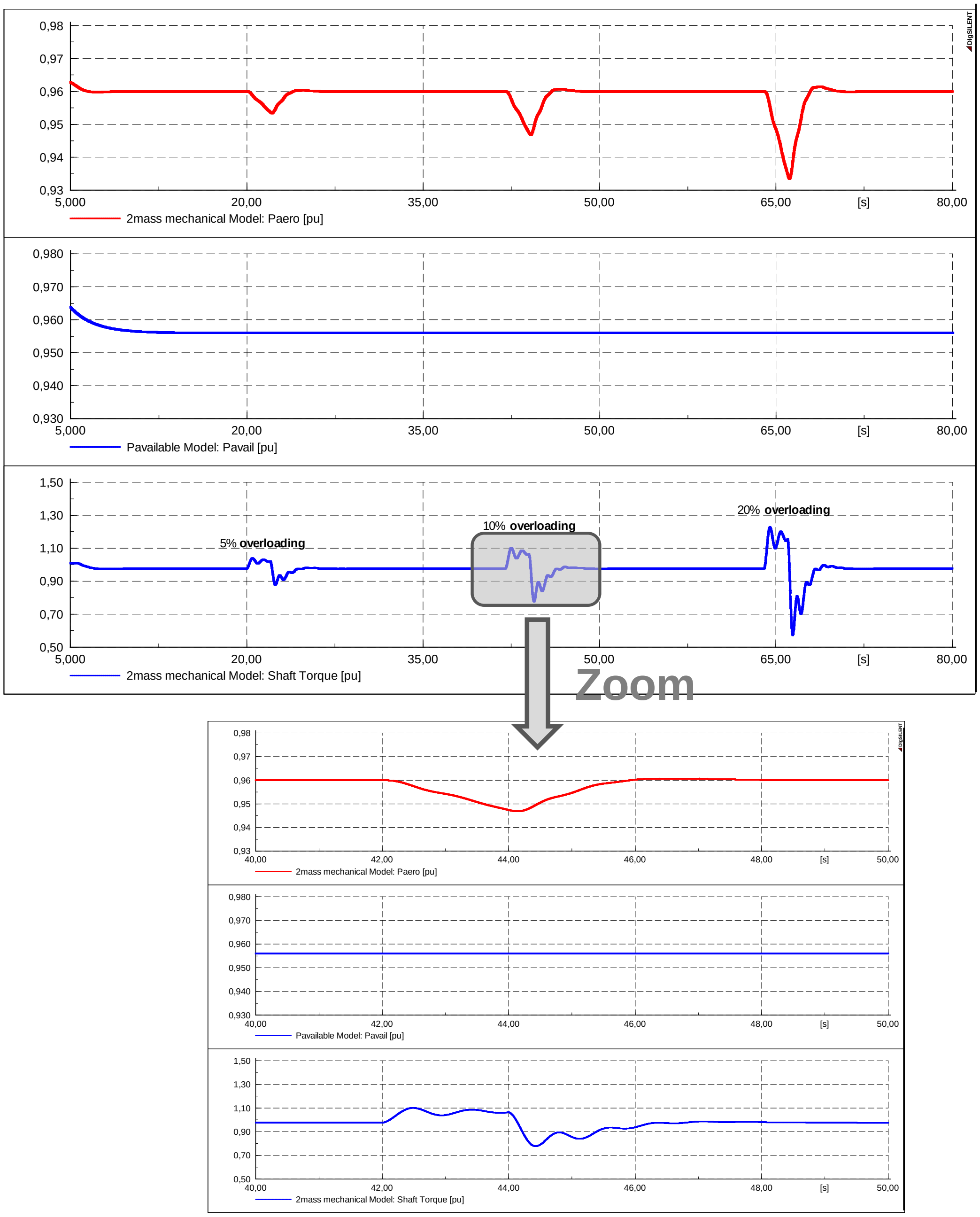

Figure 30: Overproduction with 5%, 10%, 20% respectively, during 2 sec at 11.5m/s (0.97pu) deterministic wind speed: aerodynamic power, available power and shaft torque.

It is worth noticing that, for wind speeds below than the rated wind speed, the aerodynamic power of the turbine is almost constant or slightly decreasing during overproduction, as result of the small decreases of rotor speed and constant pitch angle. For wind speeds higher than the rated speed, the aerodynamic power is increasing during overproduction because of the increase in the pitch angle.

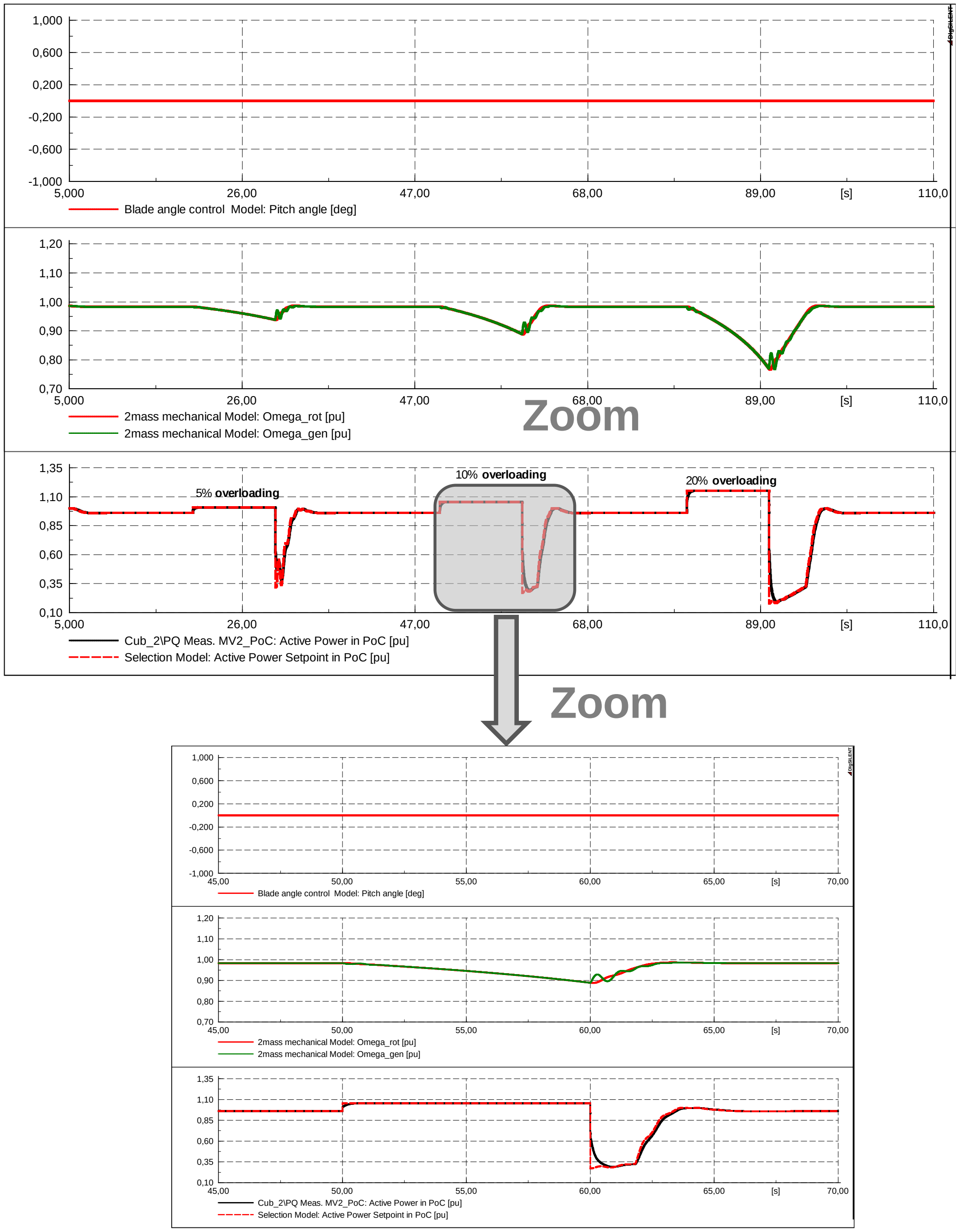

Figure 31: Overproduction with 5%, 10%, 20% respectively, during 10 sec at 11.5m/s (0.97pu) deterministic wind speed: pitch angle, generator and rotor speed, active power and its setpoint.

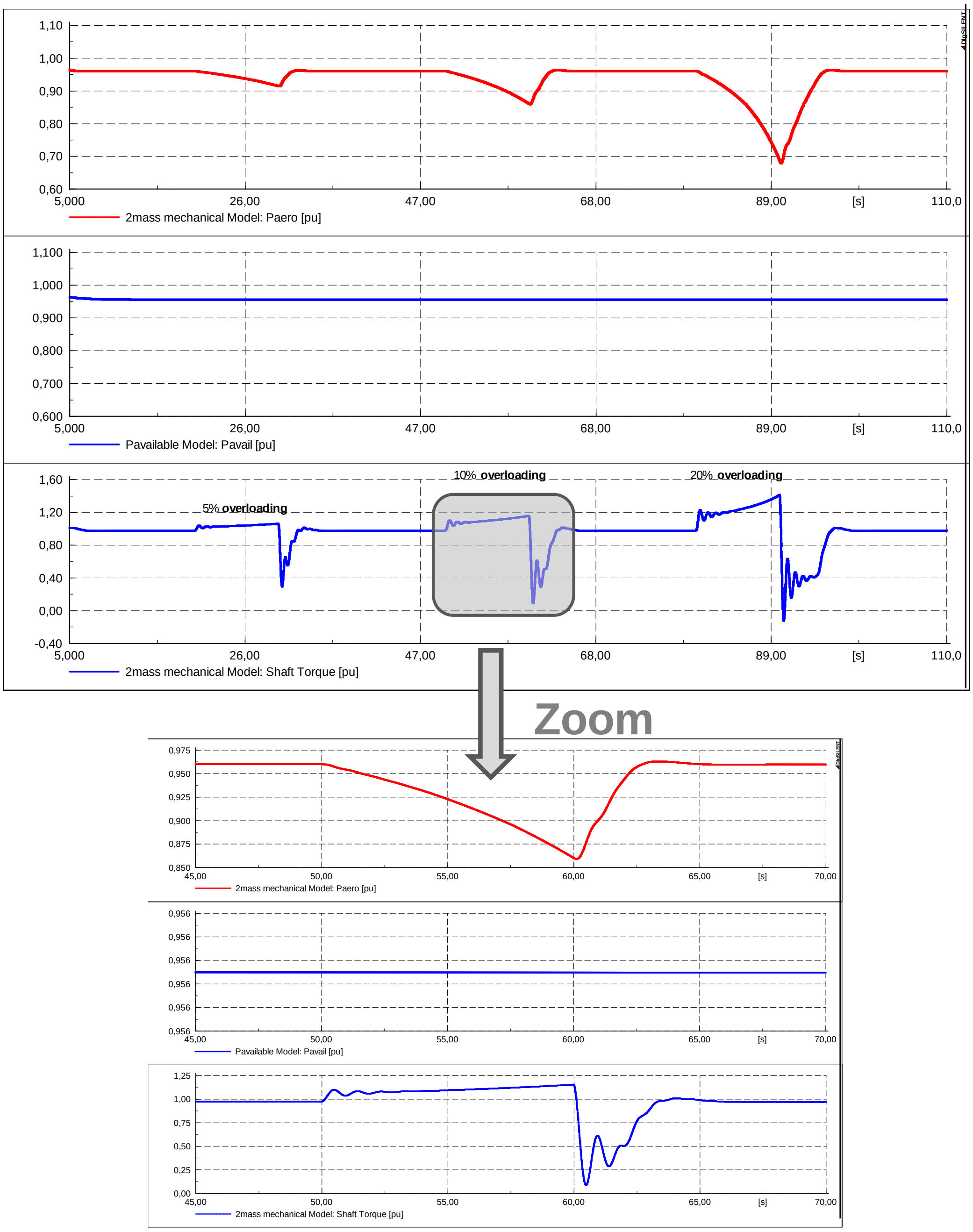

Figure 32: Overproduction with 5%, 10%, 20% respectively, during 10 sec at 11.5m/s (0.97pu) deterministic wind speed: aerodynamic power, available power and shaft torque.

Table 4 summarizes the results for speed and electrical power deviation during overproduction for different wind speeds below the rated and for different overproduction steps and periods.

6 m/sec – 0.51 pu		
Overloading (2 sec)	Dw [pu]	DP [pu]
5%	0,0021	0,0113
10%	0,0035	0,0213
20%	0,0067	0,0389
8 m/sec – 0.68 pu		
Overloading (2 sec)	Dw [pu]	DP [pu]
5%	0,0025	0,0502
10%	0,0049	0,0822
20%	0,0103	0,1245
8 m/sec – 0.68 pu		
Overloading (10 sec)	Dw [pu]	DP [pu]
5%	0,0127	0,0724
10%	0,0255	0,1023
20%	0,052	0,1647
8 m/sec – 0.68 pu		
Overloading (30 sec)	Dw [pu]	DP [pu]
5%	0,0395	0,0967
10%	0,0804	0,151
20%	0,176	0,2615
11.5 m/sec – 0.98 pu		
Overloading (2 sec)	Dw [pu]	DP [pu]
5%	0,0066	0,1347
10%	0,0132	0,2702
20%	0,0271	0,5383

Table 4: Speed and power deviations during overproduction for wind speeds below the rated and for different overproduction steps and periods.

The table reflects the following concluding remarks:

- higher the overproduction step, higher the deviation in speed and electrical power are.

- larger the overproduction period, higher the deviation in speed and electrical power are.
- for the same overproduction period, higher the wind speed, higher the deviation in speed and power are.
- in the case of 11.5m/s (0.97pu), the deviation in power can get up to 50% of the nominal turbine's power for a 20% overproduction, which might create significant stress in the turbine.

Temporary overproduction in full load operation

Figure 33, Figure 34, Figure 35 and Figure 36 illustrate the results for operation at 13m/s (1.1pu) wind speed and demanded overproduction duration time of 2 sec and 10 sec, respectively. Notice that the wind turbine manages to generate a temporary active power overproduction by decreasing the pitch angle and the generator speed. Contrary to the case of partial load operation, the aerodynamic power is increasing during the overproduction and consequently there is no recovery period.

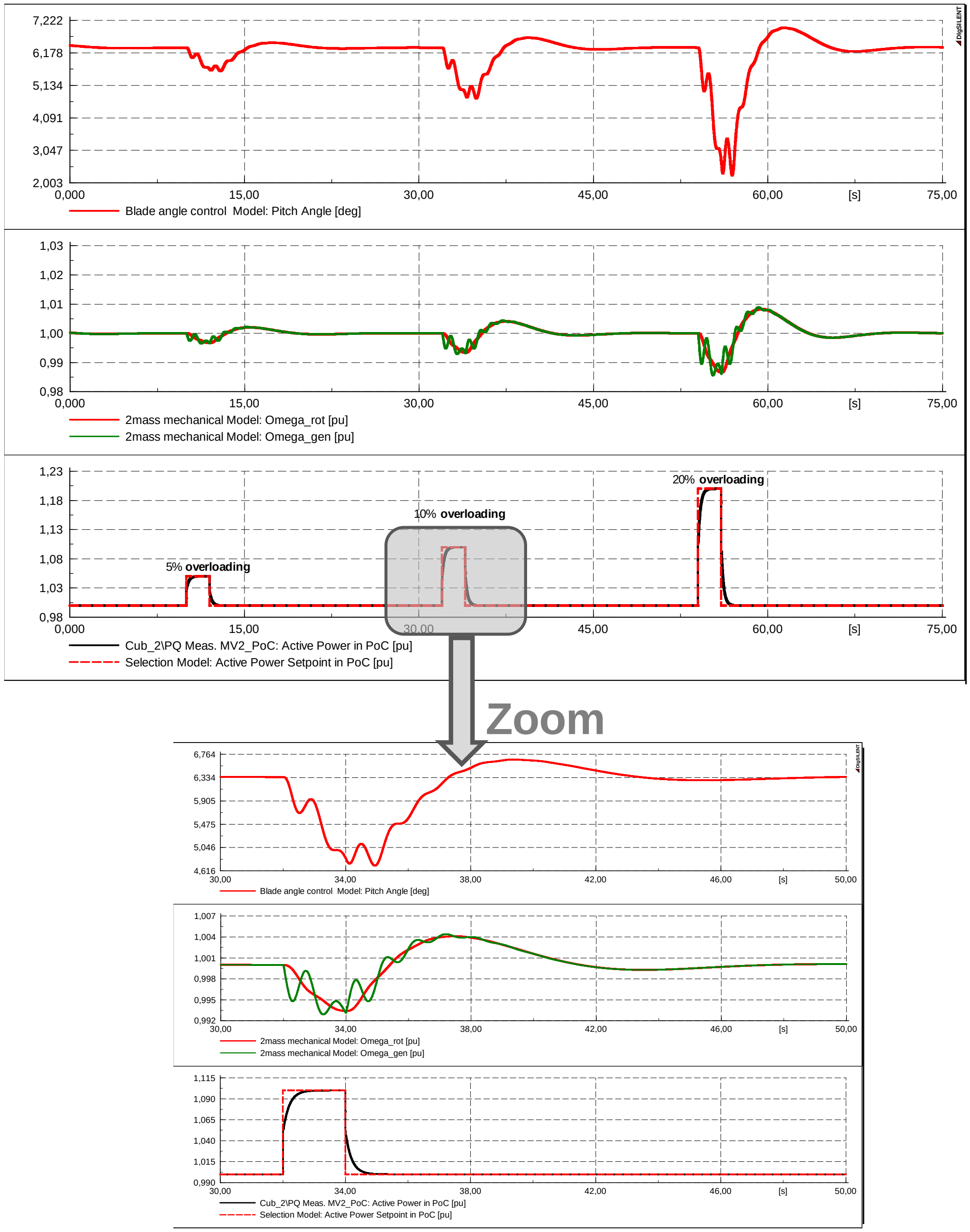

Figure 33: Overproduction with 5%, 10%, 20%, respectively, during 2 sec at 13m/s (1.1pu) deterministic wind speed: pitch angle, generator and rotor speed, active power and its setpoint.

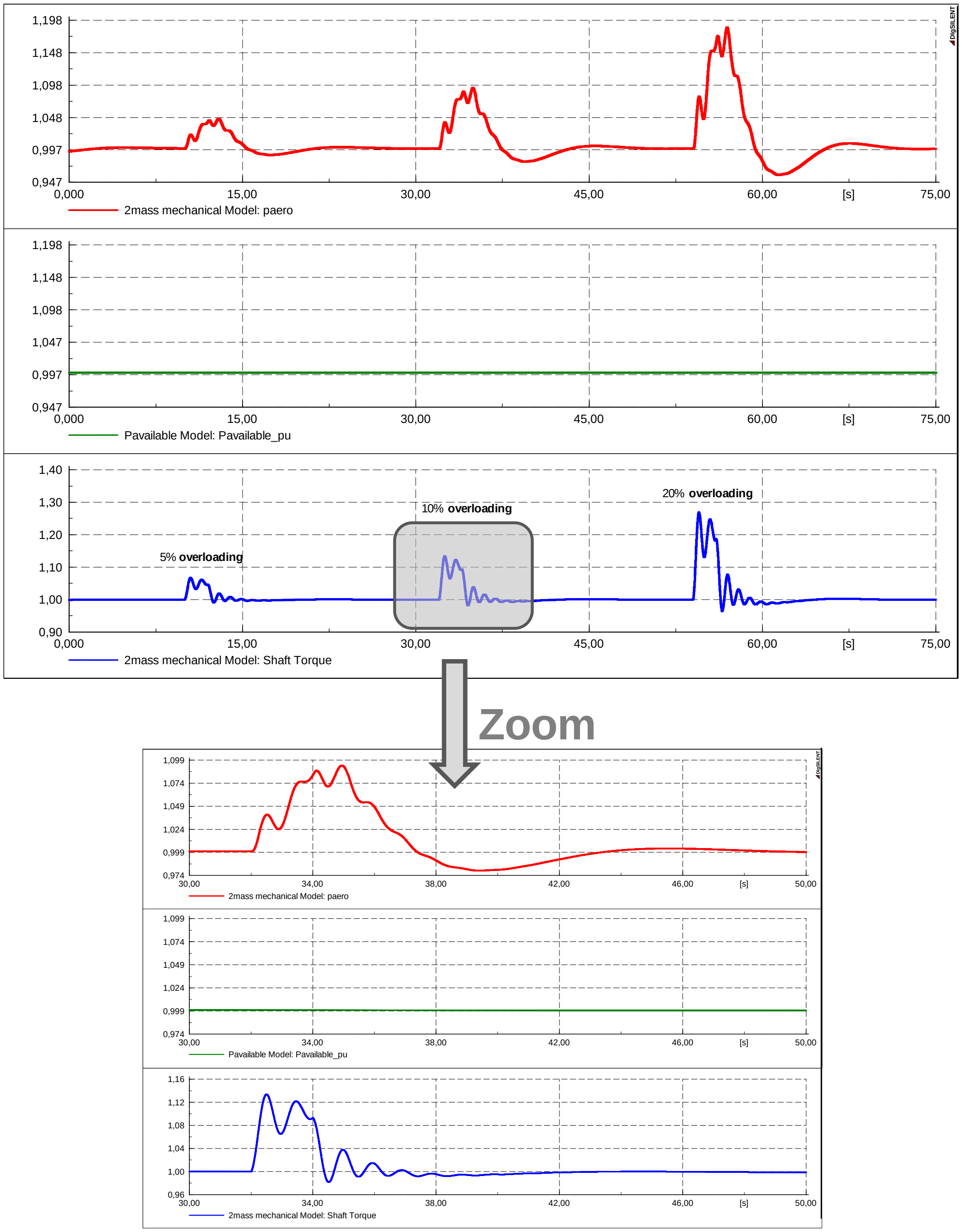

Figure 34: Overproduction with 5%, 10%, 20%, respectively, during 2 sec at 13m/s (1.1pu) deterministic wind speed: aerodynamic power, available power and shaft torque.

The higher the overproduction, the deeper the drop in the pitch angle and the generator speed. The longer the overproduction period, the longer the time with inactive pitch controller (zero pitch angle) is. The shaft torque is increased during the temporary overproduction: the higher the temporary overproduction the higher the shaft torque is.

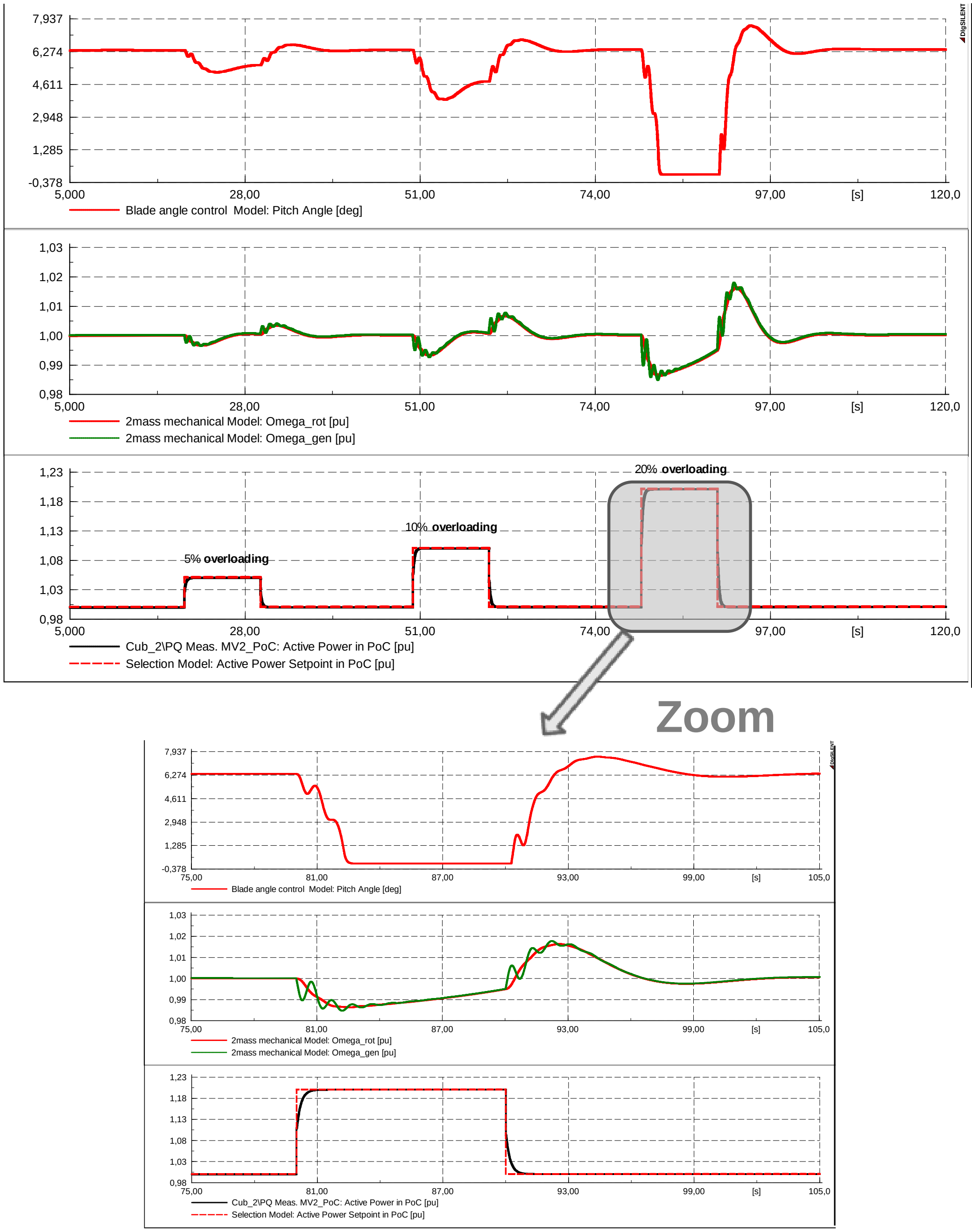

Figure 35: Overproduction with 5%, 10%, 20% respectively, during 10 sec at 13m/s (1.1pu) deterministic wind speed: pitch angle, generator and rotor speed, active power and its setpoint.

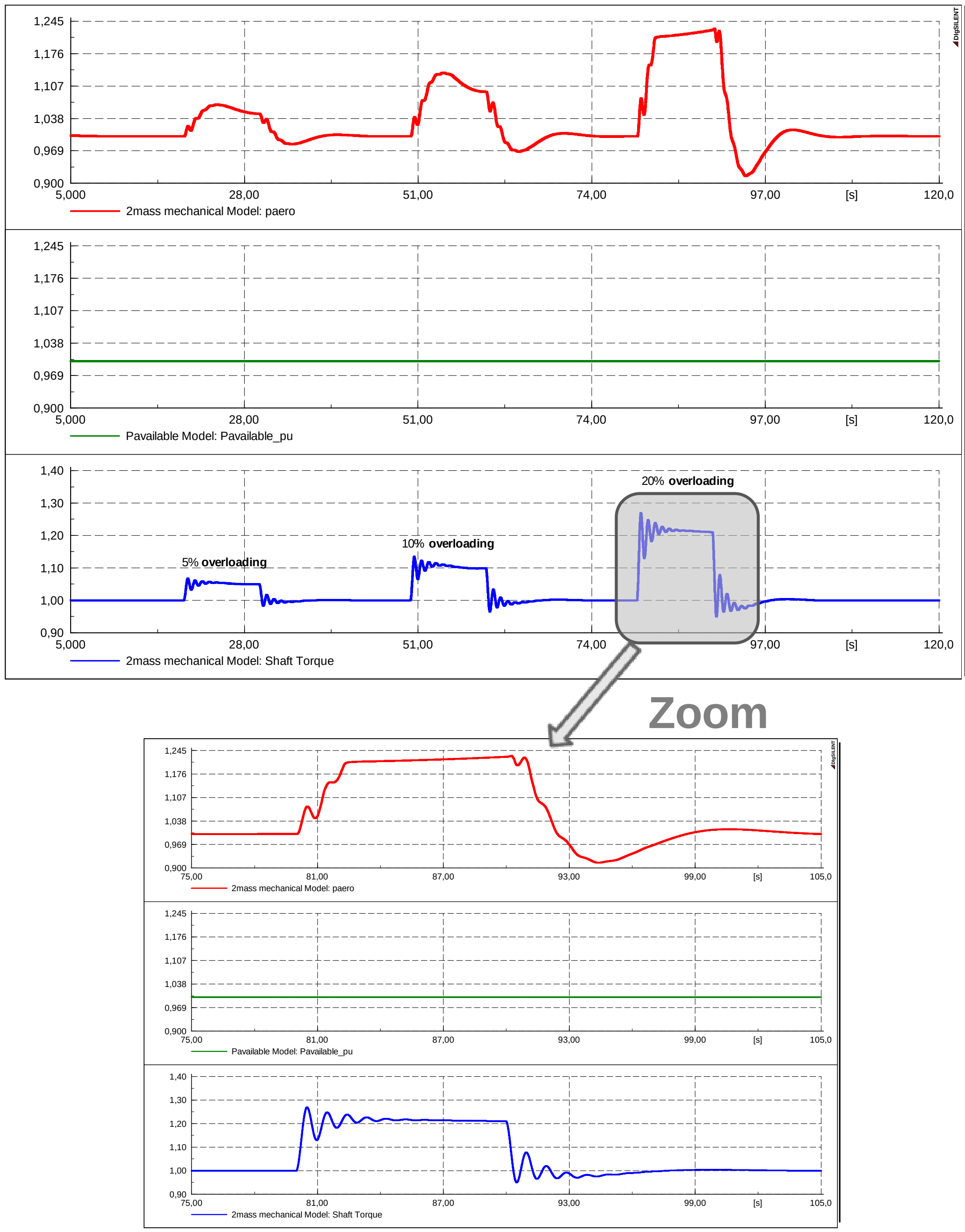

Figure 36: Overproduction with 5%, 10%, 20% respectively, during 10 sec at 13m/s (1.1pu) deterministic wind speed: aerodynamic power, available power and shaft torque.

Conclusions and outlooks

This report presents a simplified wind turbine model for a variable speed wind turbine with full scale power converter. This model follows the basic structure of the Type 4 standard wind turbine model proposed by the IEC Committee in the IEC 61400-27-1. Moreover it includes several adjustments and extensions in order to represent the power support capability of modern wind turbines, similar to conventional power plants.

The performance of the proposed wind turbine model is assessed and evaluated through a set of simulations, which reflect the dynamic features of the wind turbine response during both normal and overproduction operation. However, further refinements of the proposed simplified wind turbine model might be required, if they are interest to the ancillary services studies.

Future studies need to be carried out, especially regarding the validation of the model, as well as its electrical and mechanical parameters, as they might reflect the wind turbine's limits in providing the desired ancillary services. Future work will be directed toward incorporating the wind turbine model into a wind power plant model together with the implementation of new control functionalities in the wind power plant control level, like inertial response, synchronising power and power system damping.

Appendix A
Parameters for the simplified Type4B wind turbine model

In this section all the user-defined parameters of the proposed wind turbine model are listed and values for a 2 MW variable speed wind turbine are provided. The rotor diameter is 80 m. An air density $\rho = 1.25\ kg/m^3$ has been used for testing the model. These parameter values have not been validated with test measurements and therefore may need to be modified based on a validation process which will be defined within the EaseWind project.

Pitch Control Block

Tpitch [s] **Blade Angle Controller Time Constant**	2,2
Tservo [s] **Servo Time Constant**	0,1
Kpitch [deg/pu] **Blade Angle Controller Gain**	-38,6
pitch_min [deg] **Min. Blade Angle**	0
rate_min [deg/s] **Closing Rate of Change Limit**	-10
pitch_max [deg] **Max. Blade Angle**	30
rate_max [deg/s] **Opening Rate of Change Limit**	10
ω_{ref} [pu] **Generator speed reference**	1

Aerodynamic Power Block

Rho [kg/m^3] **Air Density**	1,225
Rotdiam [m] **Rotor diameter**	80

2 Mass Mechanical Block

Inertia of Generator [kgm^2]	**Jgen**	151
Inertia of Wind Turbine Rotor [kgm2]	**Jrot**	8682000
Low speed shaft stiffness [Nm/rad]	**K_{LS}**	111360000
Shaft Damping [Nm/rad/s]	**C**	329670
Power base [MW]	**Pbase**	2000
Nr. of pole pairs	**Npp**	2
Gear ratio	**Ngear**	96

The free-free frequency is:

$$f_{free-free} = \frac{1}{2\pi} \cdot \sqrt{\frac{K_{LS}}{J_{eq}}}$$

while the free-fast frequency is:

$$f_{free-fast} = f_{free-free} \cdot \sqrt{\frac{J_{eq}}{J_{rot}}}$$

where Jeq is the equivalent inertia of the drive train model determined by:

$$J_{eq} = \frac{J_{rot} \cdot N_{gear}^2 \cdot J_{gen}}{J_{rot} + N_{gear}^2 \cdot J_{gen}}$$

Based on the physical values indicated in the previous table for generator inertia, rotor inertia and shaft stiffness, the free-free frequency and the free-fast frequency are:

$$f_{free-free} = 1.53\,Hz \quad and \quad f_{free-fast} = 0.57\,Hz$$

For the Type 4 wind turbines, the generator is decoupled from the rest of the electrical system due to the full scale converters. According to [6], a suitable choice for the base in this case is preferably related with the nominal operation of the wind turbine, namely the speed base on the low speed shaft is equal with the rated mechanical speed:

$$\omega_{baseLS} = \omega_{mech,rated}$$

The constants of inertia in pu are then calculated as:

$$H_{pu,rot} = \frac{1}{2} \cdot \frac{J_{rot} \cdot \omega_{mech,rated}^2}{P_{base}}$$

$$H_{pu,gen} = \frac{1}{2} \cdot \frac{J_{gen} \cdot \omega_{gen,rated}^2}{P_{base}}$$

where $\omega_{gen,rated} = \omega_{mech,rated} \cdot N_{gear}$

The shaft stiffness in [pu/mech. rad] is then calculated as:

$$K_{pu/mec.rad.LS} = 4\pi^2 f_{free-free}^2 \frac{H_{pu,rot} \cdot H_{pu,gen}}{H_{pu,rot} + H_{pu,gen}}$$

H_{pu_gen} [pu] **Inertia Constant of Generator**	1,07
H_{pu_rot} [pu] **Inertia Constant of Wind Turbine Rotor**	6,65
$K_{pu/mec.rad.LS}$ [pu/mech.rad] **Shaft Stiffness**	85.265
C_{shaft} [pu] **Shaft Damping**	4 *see comment below

* The value of the Shaft Damping for the 2 Mass Mechanical Block is defining at a great extent the response of the mechanical model during transient events and has to be carefully defined. Based on the IEC approach to standard models for Type 4B, this parameter in principle includes the damping added to the system by dedicated control in order to avoid possible torsional oscillations excited in the shaft system. The value of 4 pu in this table is sufficient for a satisfactory response of the model during wind speed gusts, however needs to be defined based on real data from the manufacturer.

Speed Measurement Filter

T [s] **Filter Time Constant**	0,2

Speed to Power Characteristic

Nr [rpm]	Electrical Power [kW]
800	29,71
(…)	(…)
1600	2000

P Control Block

Kpm [ ] **Power measurement filter gain**	1
Ttr [s] **Power measurement filter time constant**	0,001
Kp [pu] **Active power control gain**	1
Tp [pu] **Active power control time constant**	0,1
Ipcmd_min [pu] **Minimum active current reference**	-1,3
Ipcmd_max [pu] **Maximum active current reference**	1,3

Selection mode

ROC [pu/s] **Rate-of-change**	0,1

Q Control Block

Tiq [s] **Time constant in power order lag**	0,01
Kq [pu] **PI Q controller prop gain**	1
Tq [pu] **PI Q controller int gain**	0,01
Kv [pu] **PI voltage controller prop gain**	1
Tv [pu] **PI voltage controller int gain**	10
Tangent_phi	0
Tpwtt [s] **P measurement filter Time constant**	0,01
Tuwtt [s] **Voltage measurement filter Time constant**	0,01
MwttPF [1/0] **(PF control /(Q control)**	0
MwttU [1/0] **(with V control / without V control)**	0
MwttOL [1/0] **(open loop/closed loop)**	0
Uref0 [1/0] **(PF and V control / other cases)**	0
Qmin [pu] **Minimum reactive power**	-0,33
Umin [pu] **Minimum voltage**	0
iQ_min [pu] **Minimum reactive current**	-1
Qmax [pu] **Maximum reactive power**	0,33
Umax [pu] **Maximum voltage**	1,1
iQ_max [pu] **Maximum reactive current**	1
Udb1 [pu] **Low voltage dead band**	0,1
Udb2 [pu]	0,2

Low voltage dead band	
iqmin [pu] **Minimum voltage dependent reactive current**	-1
iqh1 [pu] **Maximum voltage dependent reactive current**	1
Kqv [] **Voltage dependent reactive current slope gain**	4
Iqpost [pu] **Post fault constant reactive current**	-0,2

Static Generator Block

Tg1 [s] **Time Constant**	0,005
Tg2 [s] **Time Constant**	0,005
Tslope1 [s] **Time Constant (0.001)**	0,001
Tslope2 [s] **Time Constant (0.001)**	0,001
Irate_min [pu/s] **Maximum current ramp rate**	-99
Irate_max [pu/s] **Maximum current ramp rate**	99

Current Limiter Block

Imax [pu] **Maximum continuous current at WT terminals**	1,23
ImaxDip [pu] **Maximum current during voltage dip at the wind turbine terminals**	1,1
M_Qpri [] **Prioritisation of q control during FRT (0: active power priority – 1: reactive power priority)**	1
iP,VDL [pu] **Lookup table for voltage dependency of active current limits**	0,01 — 0,5678908 0,5 — 0,5678908 0,9 — 1,132475 0,901 — 1,15 1, — 1,3 1,1 — 1,3

iQ,VDL [pu] **Lookup table for voltage dependency of reactive current limits**	0,1 / 1, 0,5 / 1, 0,9 / 0,2 0,901 / 1,15 1, / 1,3 1,1 / 1,3

Pavailable Block

Kwind [] **Wind speed measurement filter gain**	1
Twind [sec] **Wind speed measurement filter time constant**	2

Grid Protection Model

MaxFrequency [pu] **Overfrequency Setting**	1,1
Time_tripMaxF [s] **Overfrequency Time Setting**	0,01
MinFrequency [pu] **Underfrequency Setting**	0,9
Time_tripMinF [s] **Underfrequency Time Setting**	0,01
MaxVoltage [pu] **Overvoltage Setting**	1,2
Time_tripMaxV [s] **Overvoltage Time Setting**	0,01
MinVoltage [pu] **Undervoltage Setting**	0,9
Time_tripMinV [s] **Undervoltage Time Setting**	3
FRTtime [s] **Time length of a voltage dip**	1

Appendix B - Steady state characteristics

Cq curves

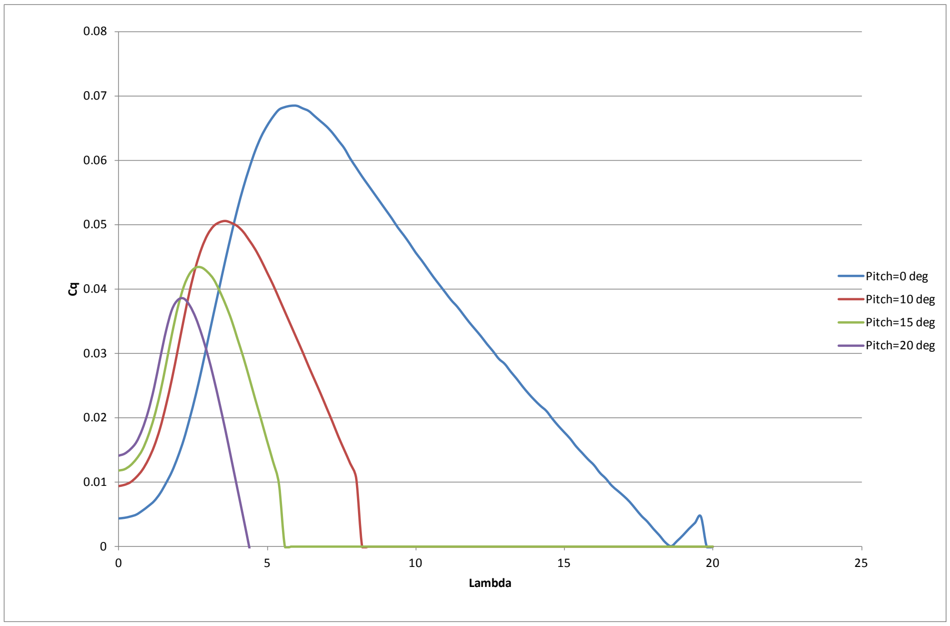

Figure 37: Cq curves for specific pitch angle values.

Steady state curves

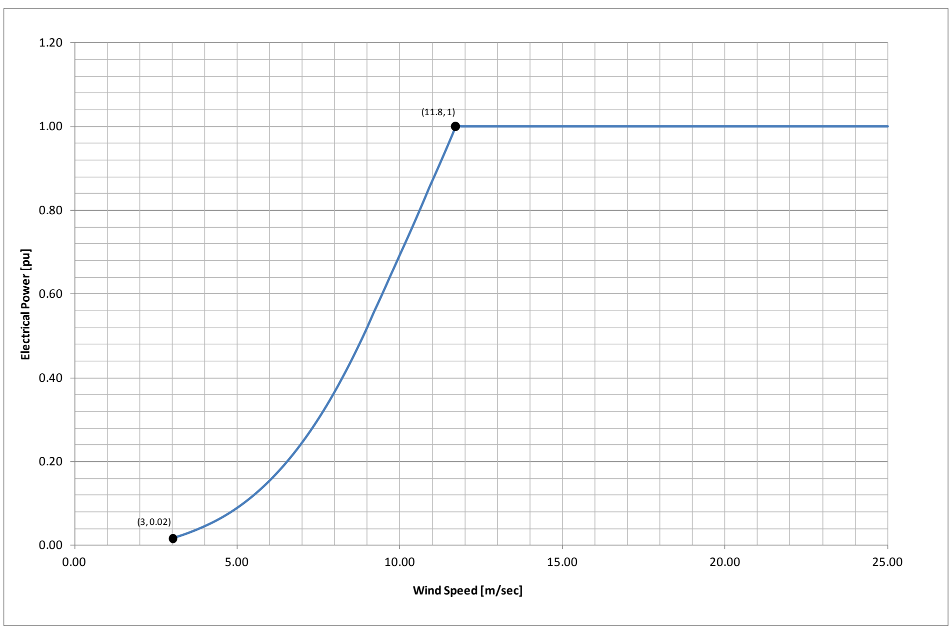

Figure 38: Electrical power [pu] versus wind speed [m/s].

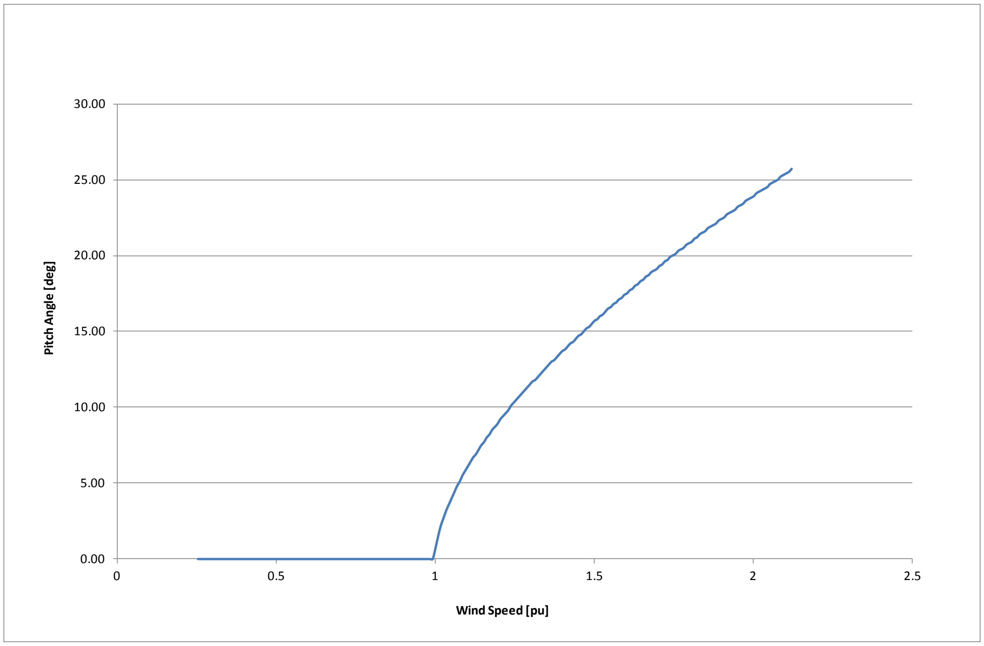

Figure 39: Pitch angle [deg] versus wind speed [pu].

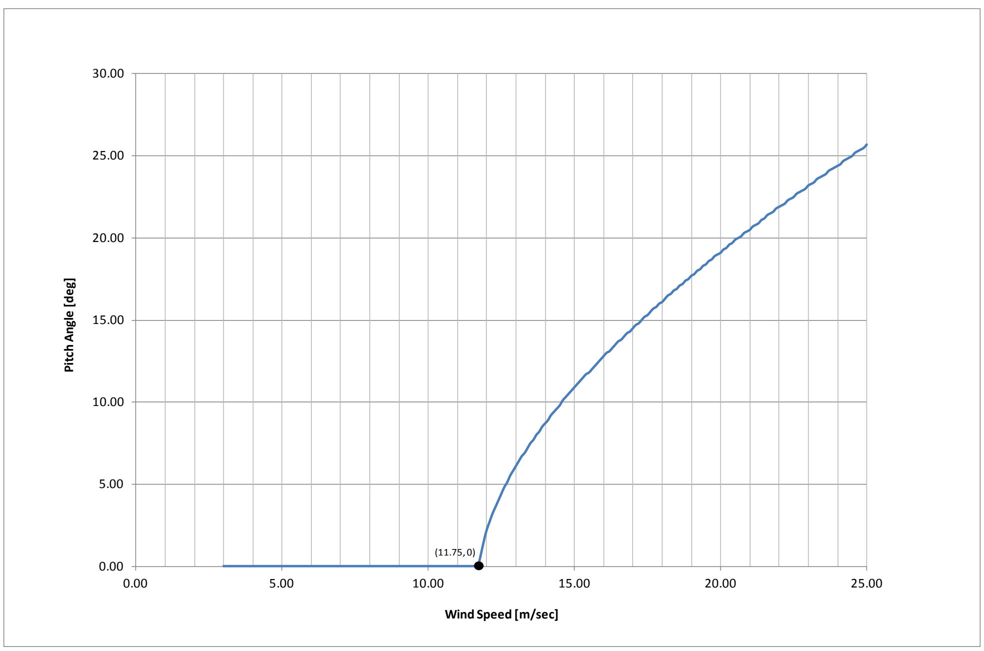

Figure 40: Pitch angle [deg] versus wind speed [m/s].

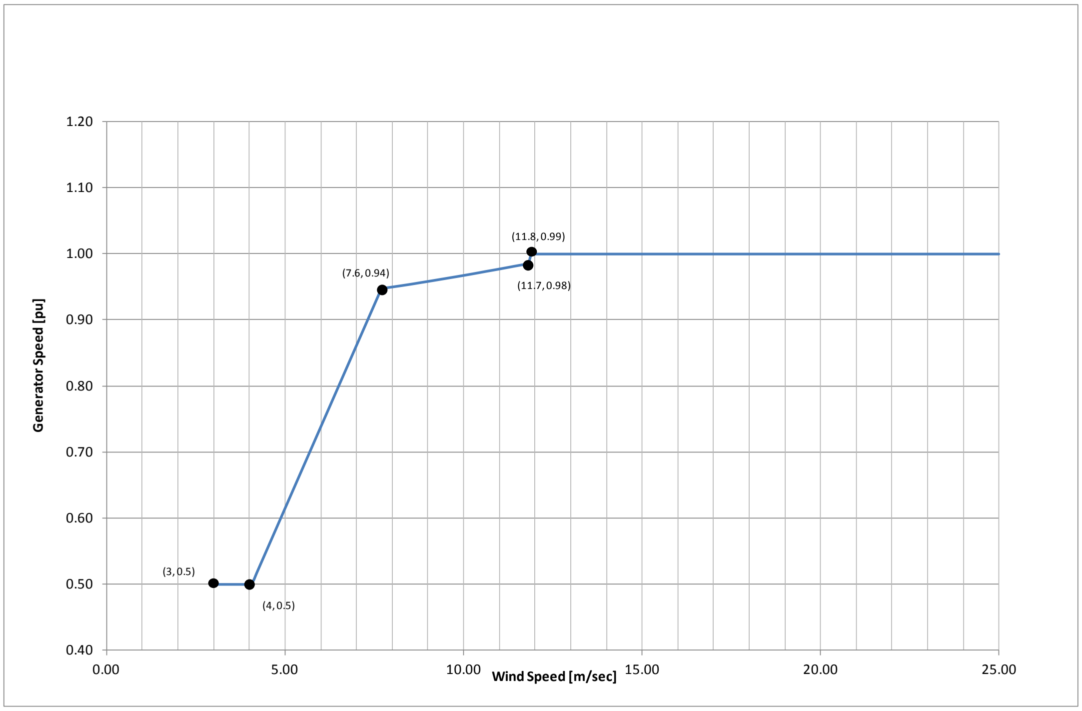

Figure 41: Generator speed [pu] versus wind speed [m/s].

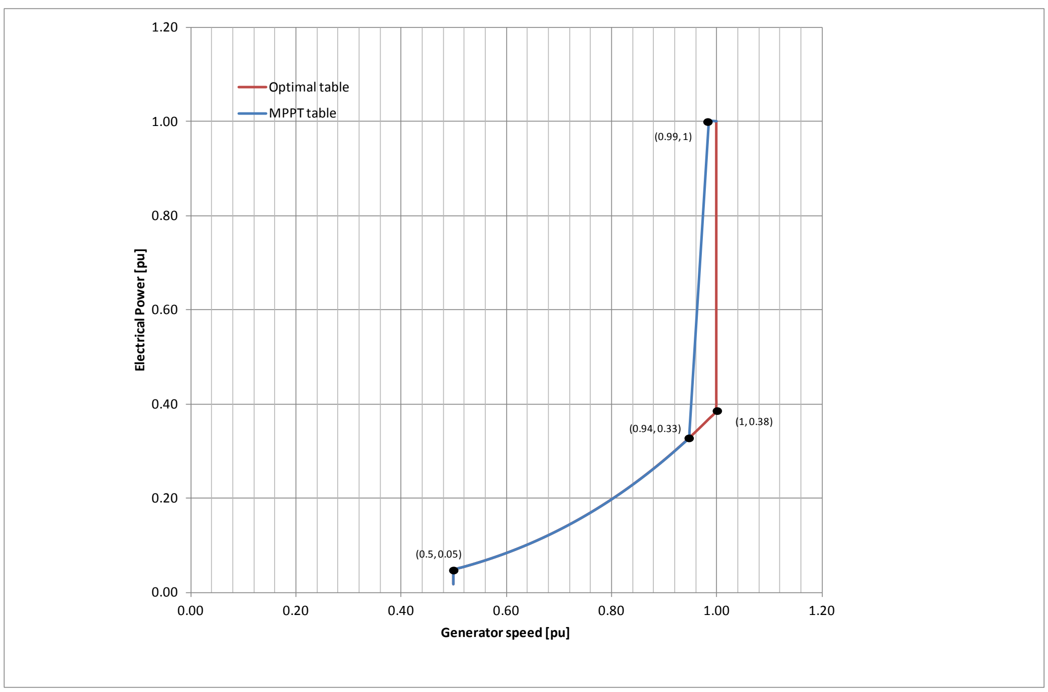

Figure 42: Electrical power [pu] versus generator speed [pu].

Acknowledgement
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