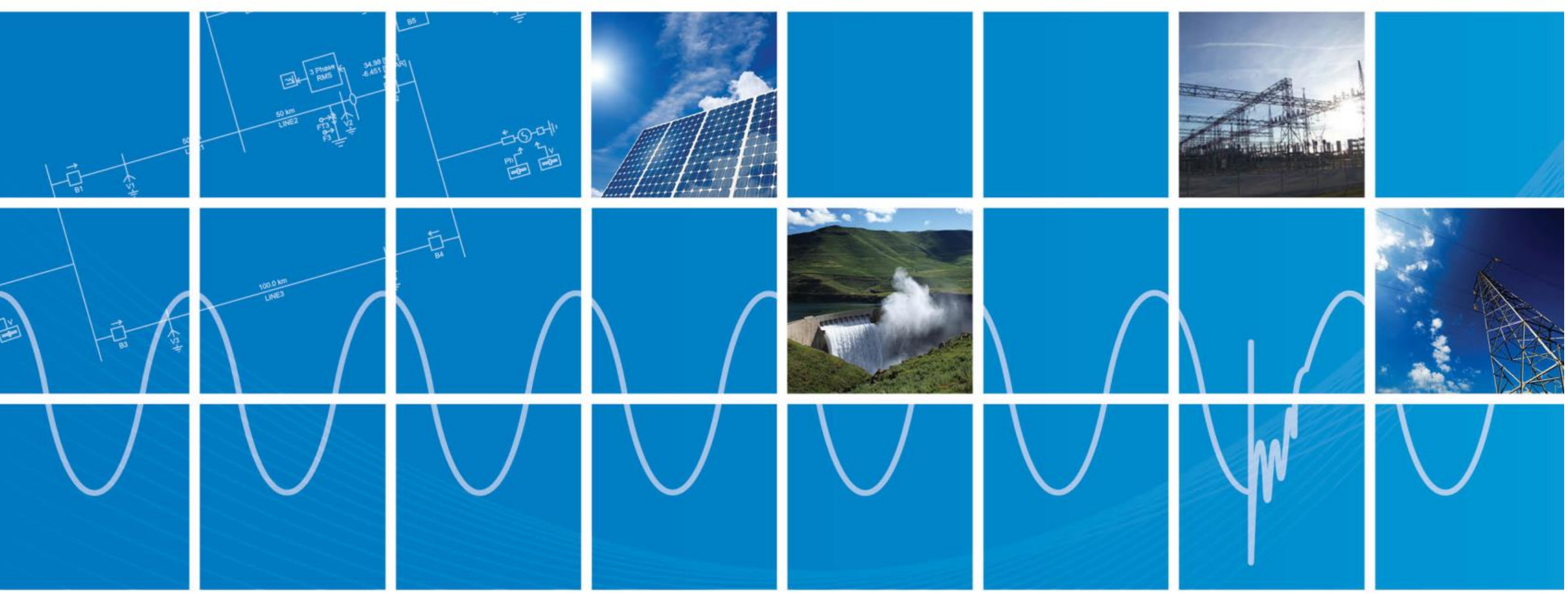
Type-4 Wind Turbine Model

For PSCAD Version v4.6 and better

December 3, 2018

Revision 3



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Contents

1 Simulation Setup

Load the workspace “WindTurbineType4Workspaces.pswx” in to PSCAD as shown in Figure 1. Loading the workspace, the simulation cases (i.e. Type4_Ave_Nov_2018.pscx and Type4_Dtl_Nov_2018.pscx) are loaded into PSCAD automatically as shown in Figure 2.

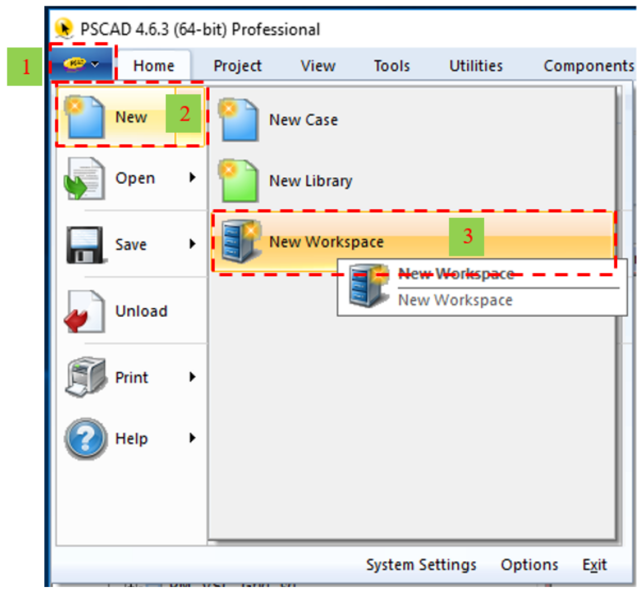


Figure 1: Steps to load the workspace into PSCAD

Clicking on the simulation name e.g. Type4_Dtl_Nov_2018.pscx in the workspace, the hierarchy tree of the active modules in the simulation are appeared as shown in Figure 2. The hierarchy tree is useful and shows the custom modules (the modules that are not from Master Library and created by user) in the simulation. And it is much easier to navigate into the custom modules. For example for the detailed model e.g. Type4_Dtl_Nov_2018.pscx the converter bridges are modeled by modules named: ConBridge_IGBT. Click on names of each module to navigate into it. Click on the + to see the rest of sub-modules.

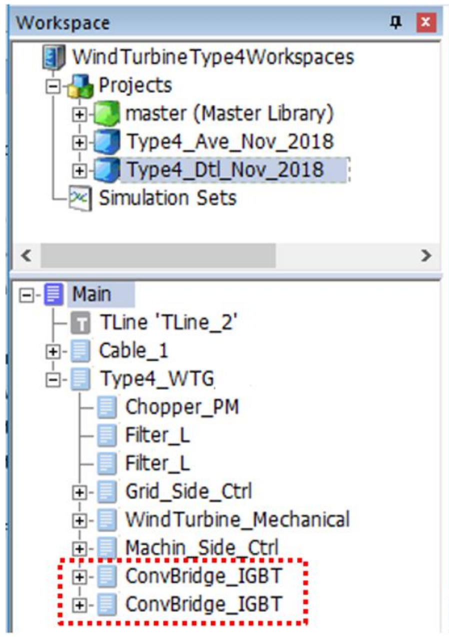


Figure 2: Workspace and hierarchy tree of the active modules in the simulation case

Click on the module named “Type4_WTG” module to see the converter circuit as shown in Figure 3.

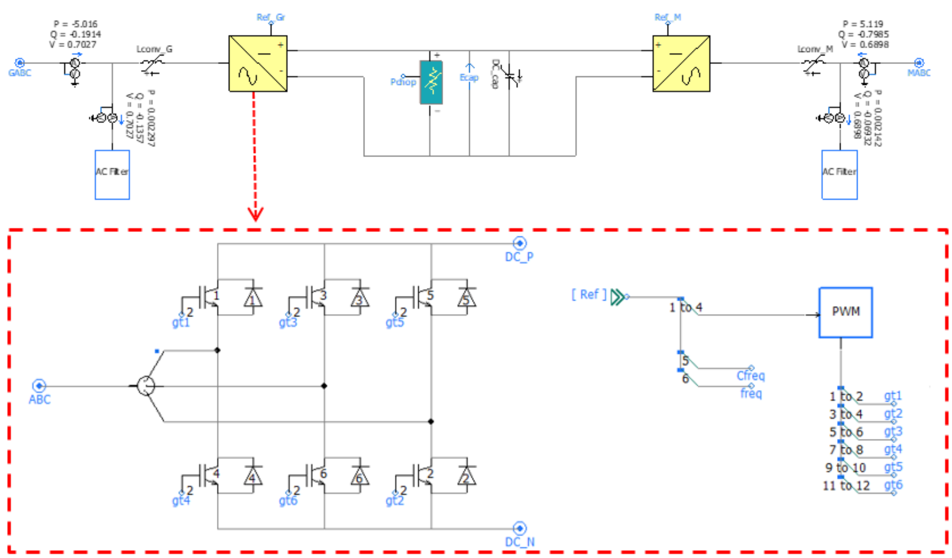


Figure 3: The converters are modelled by IGBT switches (detailed) in the Type4_Dtl_Nov_2018.pscx case

Figure 4 shows the workspace the hierarchy tree of the active modules in the simulation case Type4_Ave_Nov_2018.pscx. Note for this simulation case the converter bridges are named as ConvBridge_Avg and modelled by equivalent current and voltage sources.

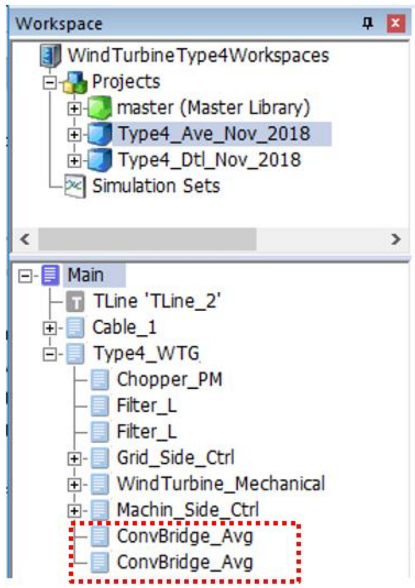


Figure 4: Workspace and hierarchy tree of active modules in Type4_Ave_Nov_2018.pscx

Click on the module named “Type4_WTG” to see the converter circuit shown in Figure 5. Click on the module named “T4_WTG_Dtl” module to see the converter circuit as shown in Figure 5.

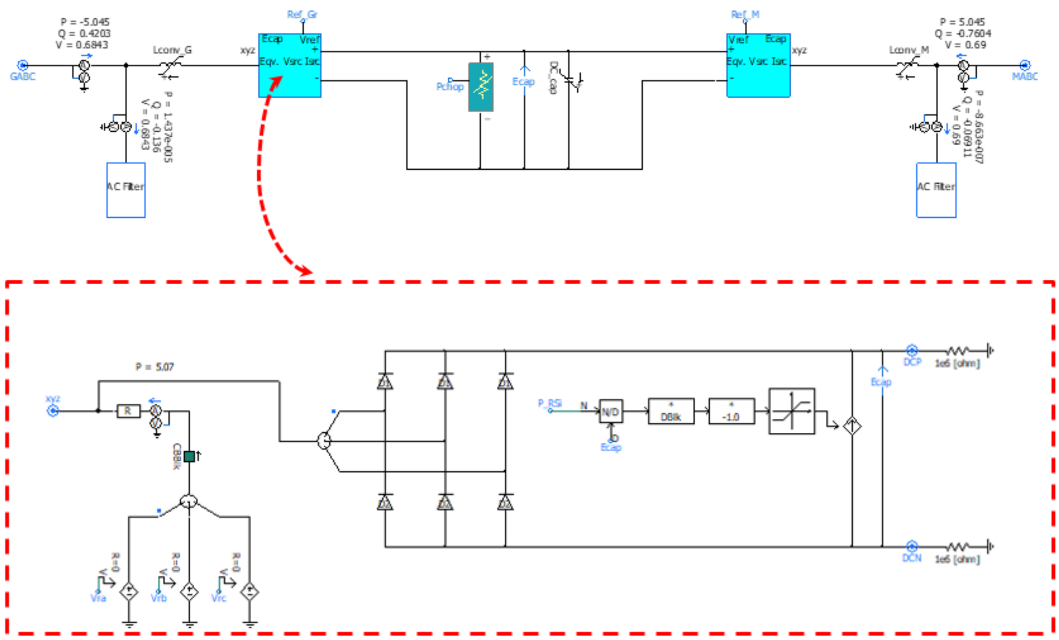


Figure 5: The converters are modelled by equivalent voltage and current sources (non-switching) in the Type4_Ave_Nov_2018.pscx

2 General Description of Type-4 Wind Turbine

Figure 6 shows type-4 wind turbine generator (WTG) which is described in two separate sections – Mechanical components (see section 2.1) and Electrical components (see section 44). The mechanical system extracts available mechanical power from the wind and yields mechanical torque. The electrical system, converts the mechanical torque to the electrical one [1]. The interface between mechanical and electrical systems is the permanent magnet (PM) machine, which converts the mechanical energy into electrical energy. The mechanical and electrical systems shown in Figure 6 by the following components:

i. Mechanical System consist of (described in section 2.1):
   a. Wind Turbine
   b. Pitch Angle Controller
ii. Electrical system consist of (described in section 4):
   a. Grid-side Converter and Controls
   b. Machine-side Converter and Controls
   c. DC-link Chopper Protection
   d. Low Pass Filters
   e. Transformer
   f. Scaling component (increases power level of WTG to model equivalent wind farm)

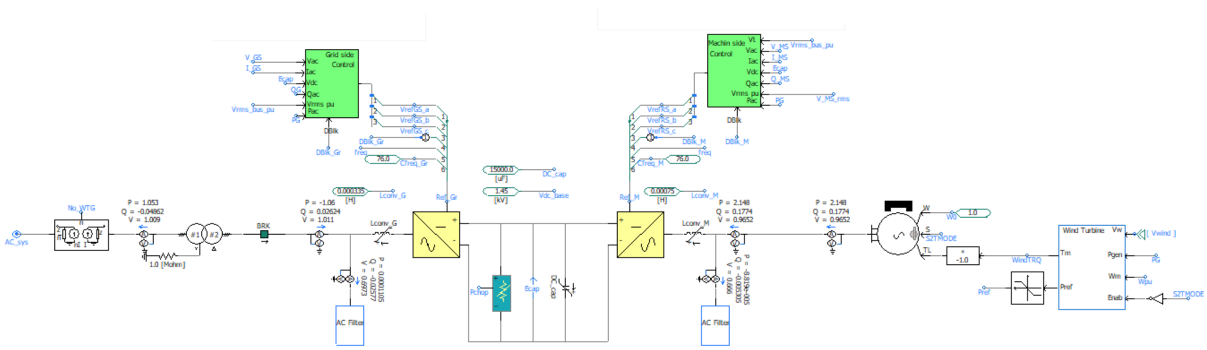


Figure 6: Electromechanical system of wind turbine

Figure 7 shows the overall power system in which a wind turbine Type-4 is connected to an equivalent voltage source representing a grid. The short circuit ratio (SCR) of the grid is 10 which represent a very strong system. This model can become unstable if connected to the grid with lower SCR at point of connection (POC).

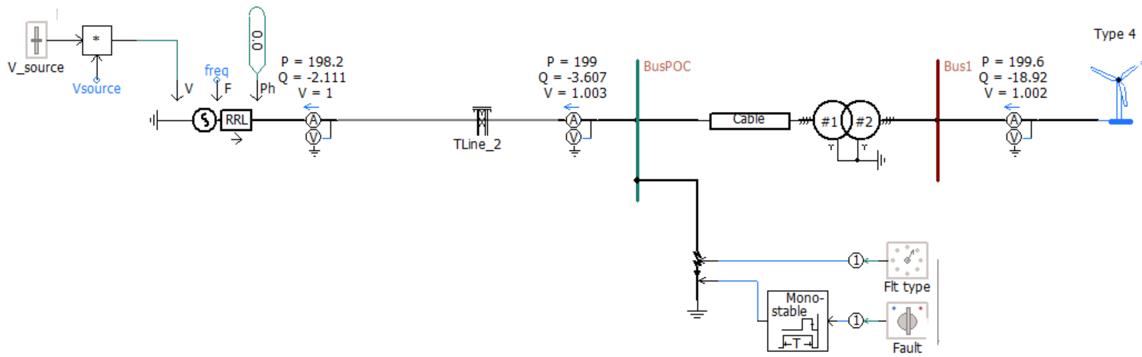


Figure 7: Overall power system with Type-4 wind turbine

Table 1 lists the input parameters with the units and values. Right click on the component and select Edit Parameters or View Properties to see the parameters.

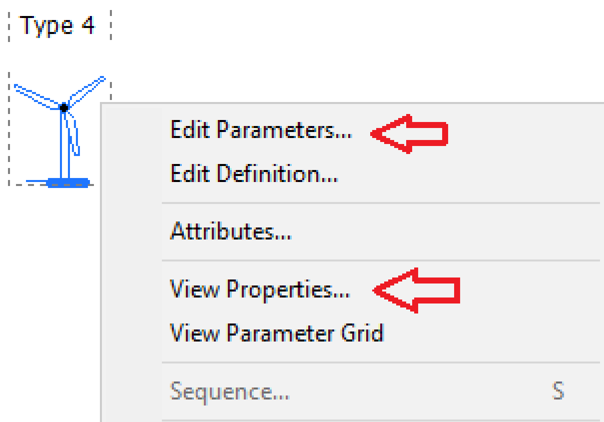


Figure 8: Type-4 wind turbine component

Table 1: Input parameters of the Type-4 wind turbine

Name	Caption	Unit	Value
Dblk	Enable/Disable the wind turbine		Dblk
Vtrf_HV	Transformer HV Rating (PCC)	kV	Vbase
No_WTG	Total number of wind turbine generator		UN
Sbase	Rated power of one unit[MVA]	MVA	2
Vrated_PM	PM Rated Voltage	kV	Vrated_PM
Vwind	Input wind speed	m/s	Vw
vWcutin	Cut-in wind speed	m/s	3
vWcutout	Cut-out wind speed	m/s	25
VRot_nom	Turbine RPM at machine nom speed [rpm]	rpm	12
freq	Nominal system frequency	Hz	freq
freq_PM	Machine base frequency	Hz	30

2.1 Start-up Sequence of the Electrical System

Figure 9 shows a simple sequence of steps to start the WTG. The start-up sequence is triggered upon closing of the AC breaker that links the WTG to the AC network. The first converter to be de-blocked is the grid-side converter. This converter operates in DC voltage control. Once the DC voltage is achieved, the Machine-side converter is de-blocked.

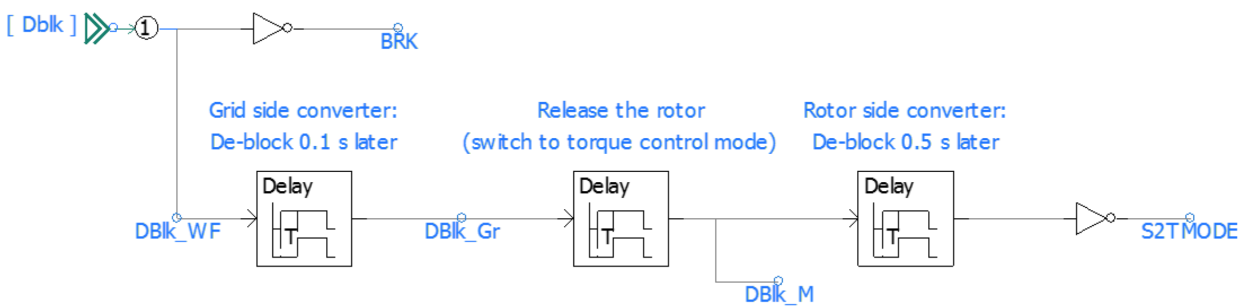


Figure 9: Start up sequence logic

3 Mechanical components

3.1 Wind turbine

The wind turbine (WT), shown in Figure 10, models the mechanical power and torque obtained from the wind and pitch controller. Right click on the module and select Edit Parameters or View Properties to see the parameters. The input parameters with their units and values are given in Table 2.

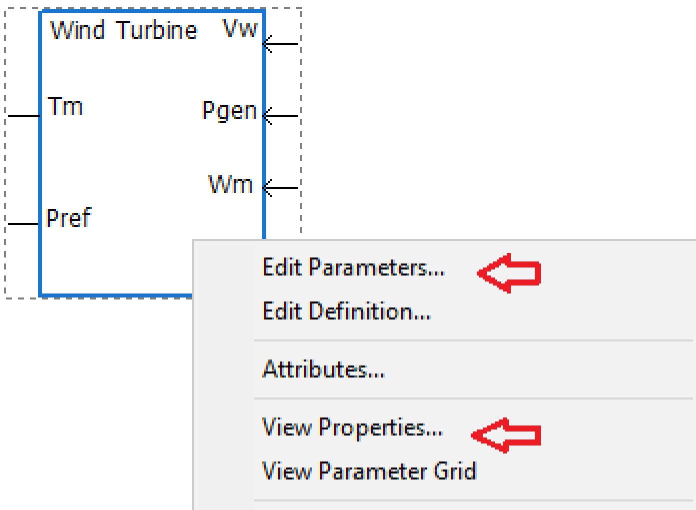


Figure 10: Wind turbine mechanical model

Table 2: Wind turbine mechanical input parameters

Name	Caption	Unit	Value
Rad_turb	Turbine radius	m	50
vWcutin	Cut-in wind speed	m/s	vWcutin
vWcutout	Cut-out wind speed	m/s	vWcutout
VRot_nom	Turbine RPM at machine nom speed	rpm	VRot_nom
Pitch_min	Minimum pitch angle	deg	0
Pitch_max	Maximum pitch angle	deg	28
Wref_sp	Reference machine speed set point	pu	W0
Pbase	Base Active power	MW	Sbase
Kp_Ptch	Regulator gain	pu	Kp_Ptch
Ti_Ptch	Regulator time constant	pu	Ti_Ptch

3.1.1 Pitch Angle Controller

The controller loop for pitch angle is represented in Figure 11. The controller consider the error in both power and speed. The cut-in and cut-out wind speeds are important parameter of the wind turbine and they define the range of wind speed for this model. When the wind speed is lower than 4 m/s, or exceed 25m/s the pitch controller.

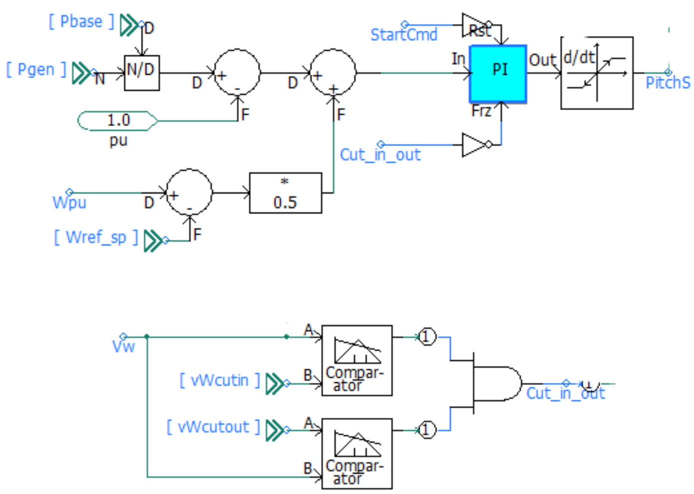


Figure 11: Pitch angle controller and cut-in and cut-out limiters

3.1.2 Wind power model

The mechanical power of wind turbine yield from the wind energy can be calculated based on the following formula [1]:

$$P = \frac{\rho}{2} \times A_r \times {V_W}^3 \times C_p(\lambda, \theta) \tag{1}$$

Where

P: mechanical power extracted from the wind turbine;

ρ: air density in $\frac{kg}{m^3}$;

A_r: area swept by the rotor blades in m^2;

V_W: wind speed in $\frac{m}{sec}$;

λ: tip speed ratio

θ: pitch angle

C_p: power coefficient, which is function of λ and θ.

C_p is a characteristic of the wind turbine that is usually provided by the manufacturer as a set of curves relating C_p to λ with θ parameters.

Under the steady state conditions, the definition of the tip-speed ratio is given by:

$$\lambda = \frac{W_{turb} \times R}{V_W} = \frac{2\pi \times n_{turb} \times R}{V_W} \tag{2}$$

The PSCAD implementation of (2) is shown in Figure 12.

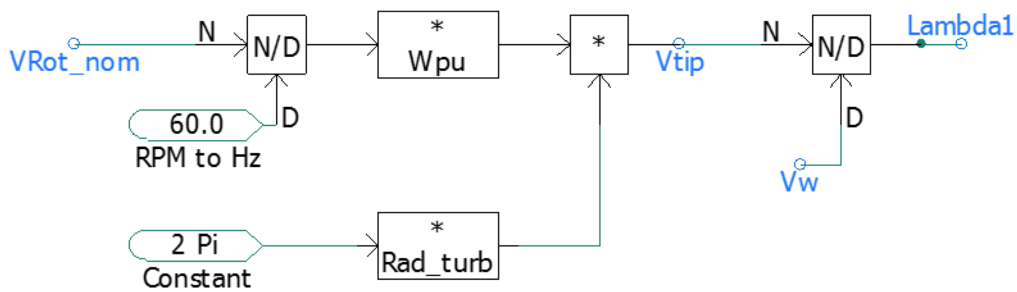


Figure 12: Tip-speed ratio calculation

The calculation of the power coefficient used in this example follows the *Cp* curves provided in [2]. The *Cp* calculation is given in terms of a fourth order polynomial of the following form:

$$C_p(\theta,\lambda) = \sum_{i=0}^{4}\sum_{j=0}^{4}\left(\alpha_{i,j}\cdot\theta^i\cdot\lambda^j\right) \qquad (3)$$

The curve gives a good approximation for values of 3 < λ < 15 and negative *Cp* are limited to -0.05. The $\alpha_{i,j}$ can be represented as a 5x5 matrix using 25 coefficients, as shown in Figure 13.

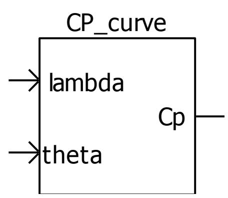


Figure 13: Look up table for polynomial function of Cp

The mechanical wind power (Pwind_pu) obtained from wind power are calculated by Equation (3). The model of the wind turbine is implemented as shown in Figure 14.

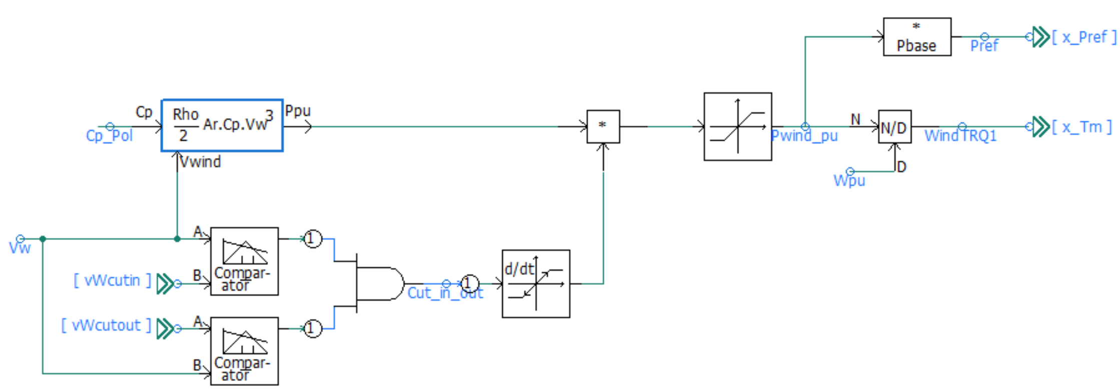
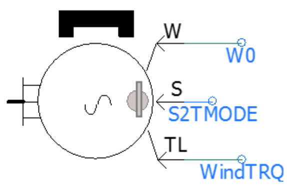


Figure 14: Mechanical power and torque of WTG

4 Electrical components

In this document the electrical part of the wind turbine is consist of permanent magnet machine (PM) and the AC-DC-AC converter.

Figure 15 shows the PM machine and its terminal descriptions. The speed of the machine 'W' can be set to a preselected value W_0. Ideally this speed should be setup close to the final steady state rotating speed which is 1 pu.



- *W: Speed input in per-unit. When machine is in speed control mode the machine runs at W0 speed.*
- *S: A switch to select speed control mode (1) or torque control mode (0).*
- *T: Torque input in per-unit. If the machine is in torque control mode then the machine computes the speed based on the inertia and damping coefficient, the input and output torques.*

(a) (b)

Figure 15: PSCAD PM machine, (a) the terminal inputs, (b) terminal descriptions

4.1 AC-DC-AC Converters

The AC-DC-AC converter is shown in Figure 16. The AC-DC-AC converter consists of:

i. Grid-side converter and controller,
ii. Machine-side converter and controller,
iii. DC-link chopper,
iv. Low pass filters,
v. Scaling component.

The grid-side converter controls the DC bus voltage, while the machine-side converter controls active power (P) at the terminal of the wind turbine. In this example both converters, operate as voltage source converters (VSC).Both converters are modelled as detailed and average (so-called non-switching) models as described in Figure 3 and Figure 5. The grid-side and machine-side controllers are described in the sections 4.1.1 and 4.1.2 respectively. The controllers are the same for both average and detailed models. The DC chopper is used to protect the DC bus from over voltages. A more detailed description of these components is provided in subsequent sections. AC filters are used on AC sides of the converters to remove some of the voltage harmonics of the two-level converters.

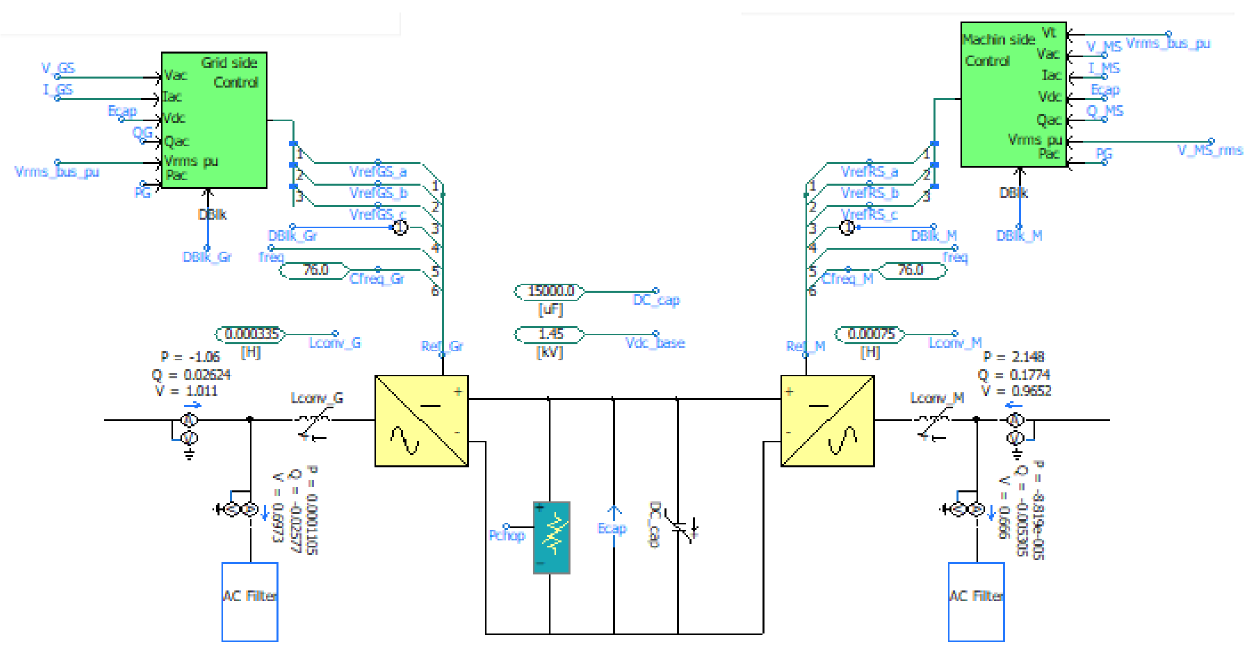


Figure 16: AC-DC-AC converter consists of grid-side, machine-side converters, DC-Link chopper, and low-pass filters

4.1.1 Grid-side controller

The grid-side control, shown in Figure 17, regulates the DC bus voltage (Ecap) and AC voltage (Vac). The reference for the AC voltage is set to 1 pu.

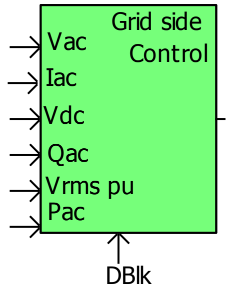


Figure 17: Grid-side control component

The grid-side controller parameters are given in Table 3.

Table 3: Grid-side control parameters

Name	Caption	Type	Unit	Value
ILimPriority	d or q axis priority: 0-Iq, 1-Id	Integer		0
Sbase	Rated MVA	Real	MVA	Sbase
freq	AC system frequency	Real	Hz	freq
Vacbase	Rated AC voltage	Real	kV	Vrated_PM
Vdc_base	Vdc_base	Real		Vdc_base
Lconv	VSC inductance	Real	H	Lconv_G
Imax_pu	Maximum per unit current	Real	pu	1.1

The per-unitization and transformation of current and voltage measurements are shown in Figure 18 and Figure 19 respectively. High reject filters with characteristic frequency of 360 Hz are added to improve the quality of dq quantities by filtering out some of the high frequency harmonics of the power electronic converter. Base quantities for the grid-side converter controls and maximum converter currents are calculated based on the rated power (Sbase) and rated voltage (Vacbase line to line, rms).

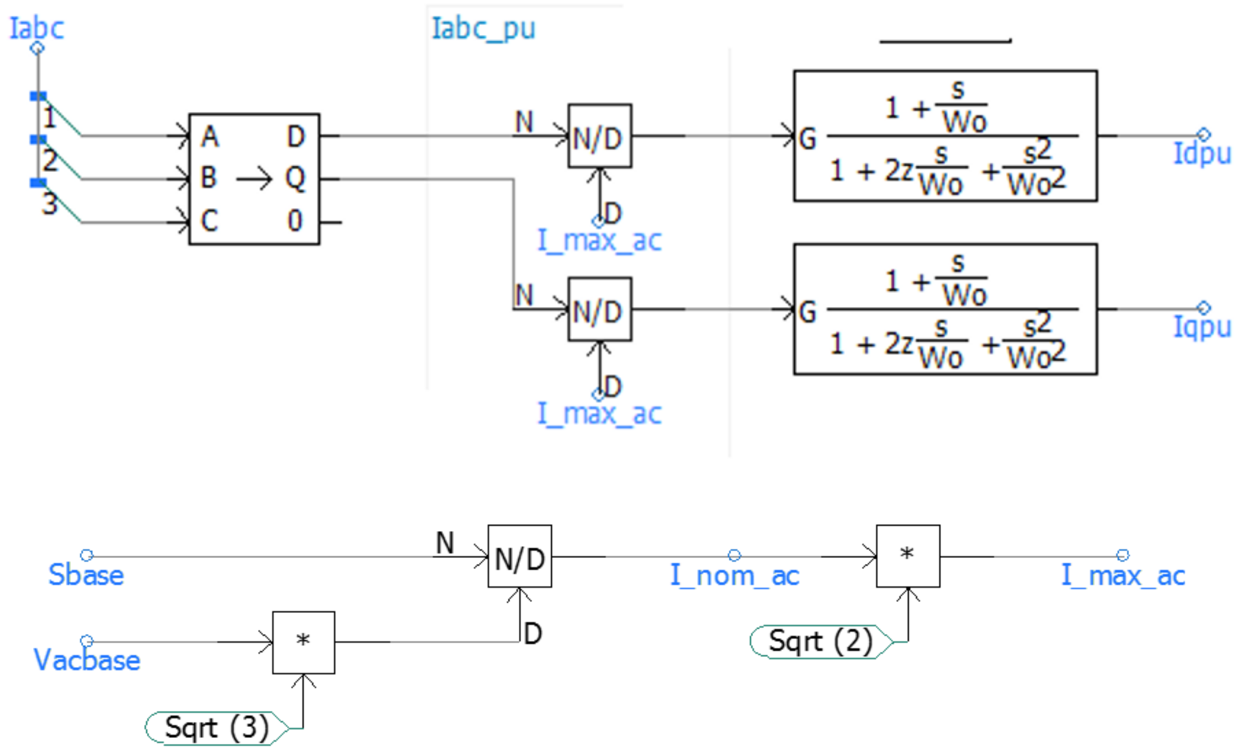


Figure 18: Current per-unitizing and transformation from abc to dq0

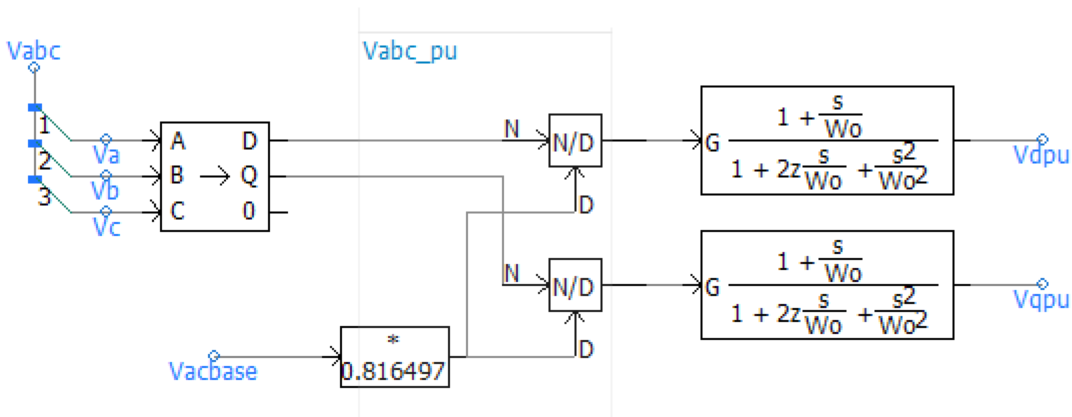


Figure 19: Voltage per-unitizing and transformation from abc to dq0

The DC bus voltage and cascaded AC voltage and reactive power (Q) controllers are shown in Figure 20 and Figure 21. These controllers generate the d-axis and the q-axis current orders (i.e. Id_ord_pu and Iq_ord_pu) for the decoupled control respectively. The sliders can be modified to change the Kp and Ti coefficients of the PI controllers in order to tune the controllers if necessary. The PI controllers are anti-windup so that the integrator never saturated. The cascaded AC voltage and reactive power (Q) controllers is able to inject reactive power during faults. The controller is utilized with a voltage dip/swell detector to increase/decrease q-axis reference current.

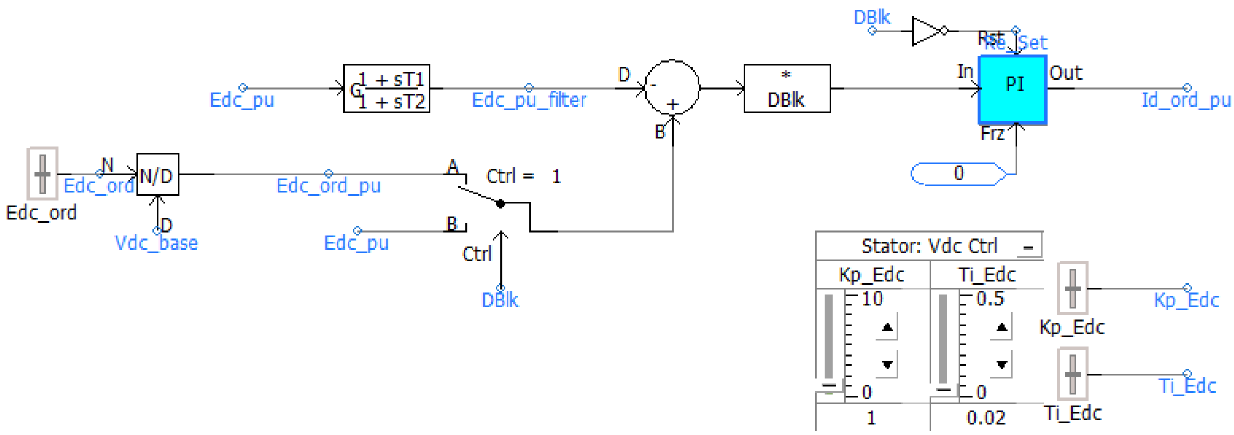


Figure 20: DC voltage controller

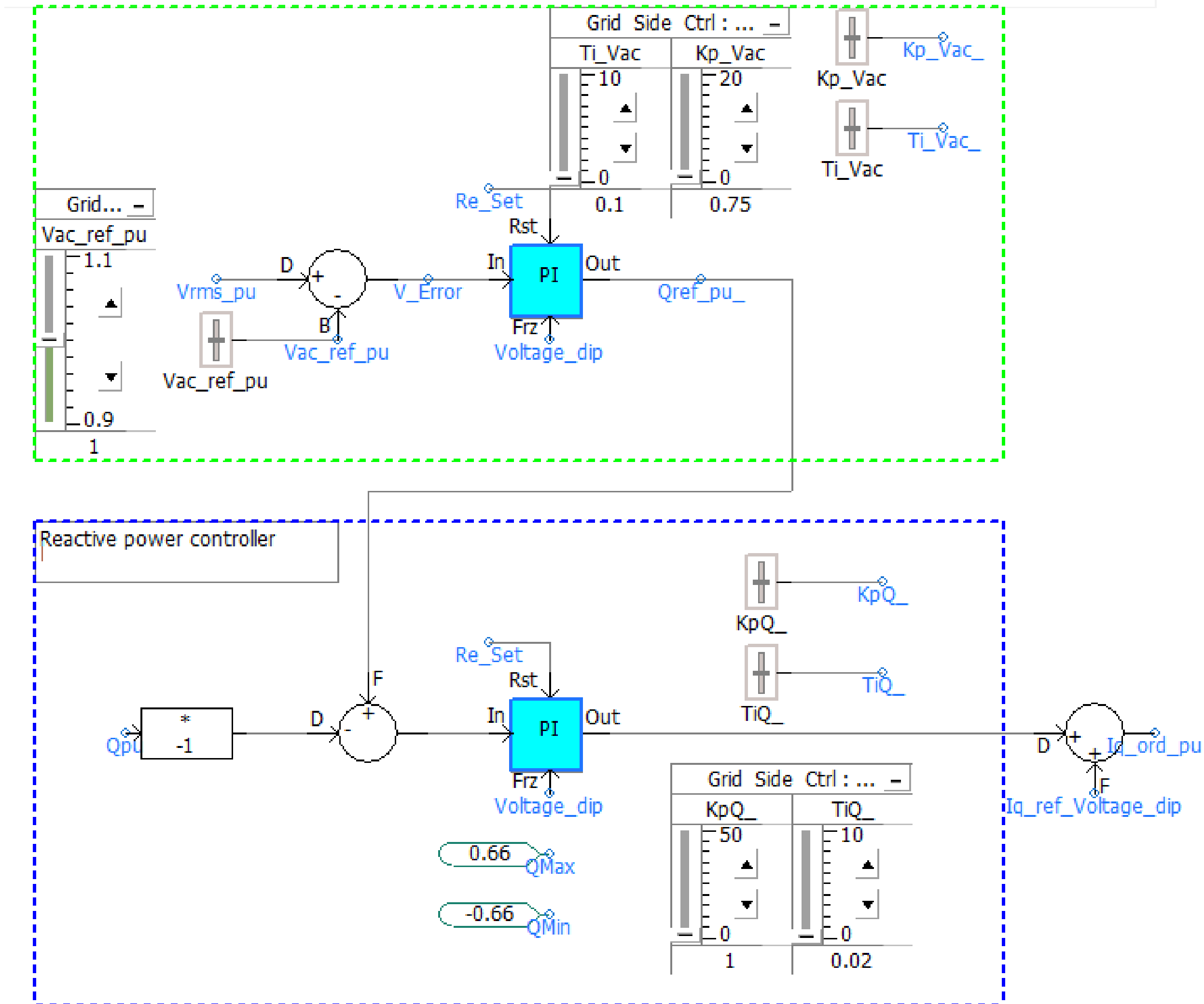


Figure 21: Cascaded AC voltage reactive power controller

For this converter, the default priority can be assigned to the d- or q- axis as shown in Figure 22. The priority is set to the q-axis as shown in Table 3 (priority signal is set to 0). If the priority is given to the d-axis (DC control), it should be set to 1. The maximum Grid-side converter current rating has been set to 1.2pu to be able to work under low voltage ride trough.

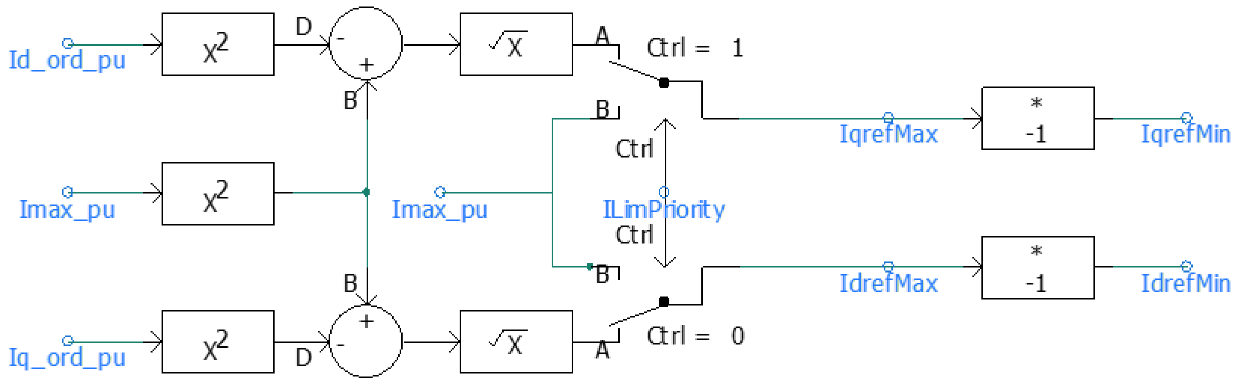


Figure 22: d- and q-axis current limit calculation

The decoupled current controls shown in Figure 23 are used to generate the converter reference voltages i.e. vd1ref and vq1ref. In order to decouple (i.e. reduce their effect on each other) the d and q axis the terms Iqpu× wLpu and Idpu× wLpu are subtracted and added to d-axis and q-axis respectively. The sliders can be modified to tune the controllers if necessary.

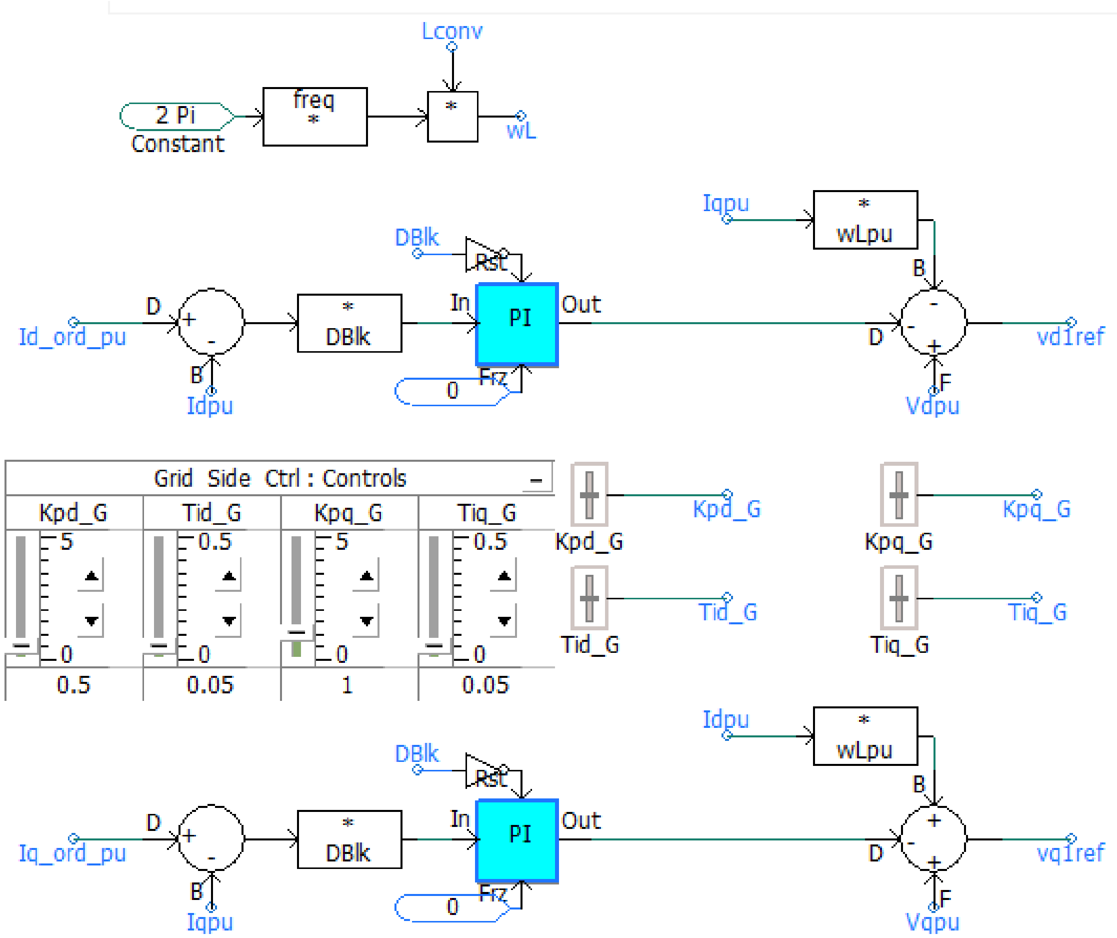


Figure 23: d- and q-axis decoupled controllers to generate the reference voltages

As shown in Figure 24, the reference voltages i.e. vd1ref and vq1ref are converted from rectangular to polar domain and the magnitude (M) is per unitized and limited to 1.15 pu. The three-phase reference voltage waveforms are obtained by applying the dq0 to abc transform to vd1ref and vq1ref, using thetaPLL as the conversion angle. Up to this point, the reference wave-shapes are calculated in per-unit using the AC voltage peak to ground as the base voltage.

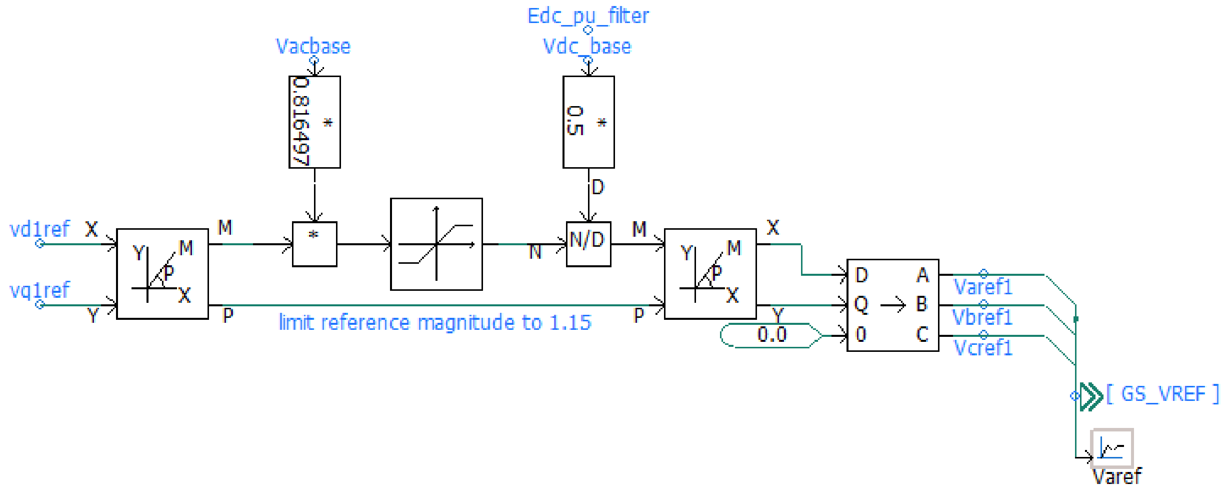


Figure 24: Reference voltages provided by grid-side controller

4.1.2 Machine-side controller

The function of the machine-side controller is to control active power (P) and AC voltage at te terminal of the PM machine to obtain required ratings at the terminals of the wind turbine. The machine-side control is shown in Figure 25 .

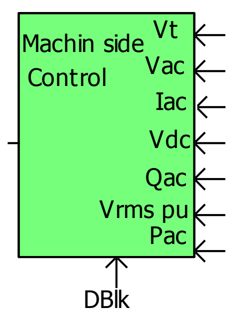


Figure 25: Machine-side control component

The rotor-side converter parameters are given in Table 4.

Table 4: Rotor-side control parameters

Name	Caption	Type	Unit	Value
ILimPriority	d or q axis priority: 0-Iq, 1-Id	Integer	-	0
Pref	Active power order	Real	pu	Pref
Q_ord	Reacitve power ordered (Qord, Mvar)	Real	Mvar	0
Sbase	Rated MVA	Real	MVA	Sbase
freq	AC system frequency	Real	Hz	freq_PM
Vacbase	Rated AC voltage	Real	kV	Vrated_PM
Vdc_base	Vdc_base	Real	-	Vdc_base
Lconv	VSC inductance	Real	H	Lconv_G
Imax_pu	Maximum per unit current	Real	pu	1.1

The machine side active power controller is shown in Figure 26. The controller is utilized with an active power drop lookup table during low voltages. This increase the stability of the WTG during faults and provides low voltage ride through (LVRT) capability.

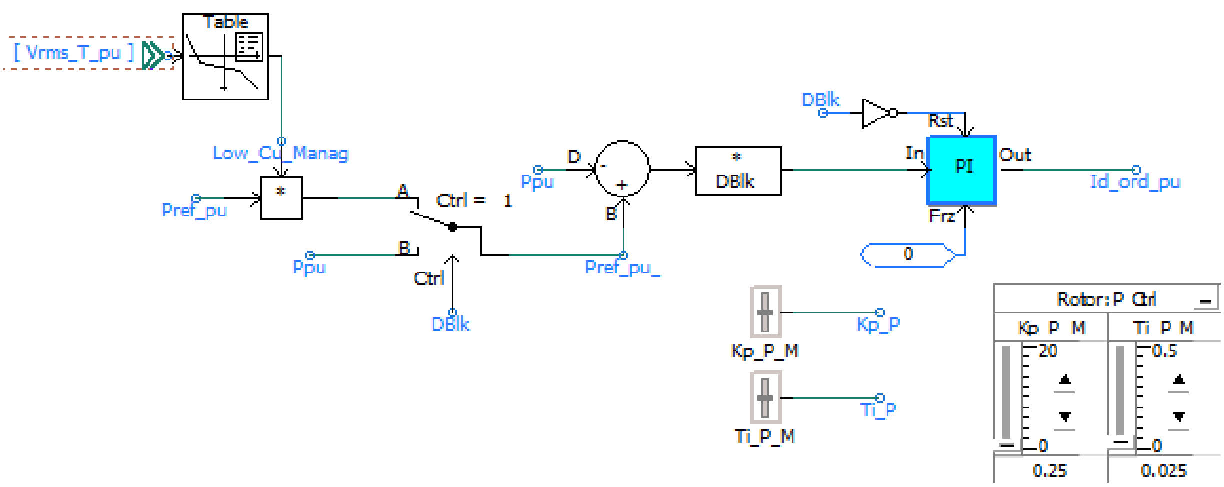


Figure 26: Machine side active power controller

The AC voltage controller is shown in Figure 27 where the reference voltage is set to 1pu.

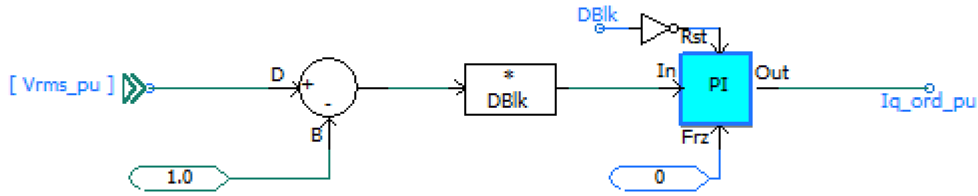
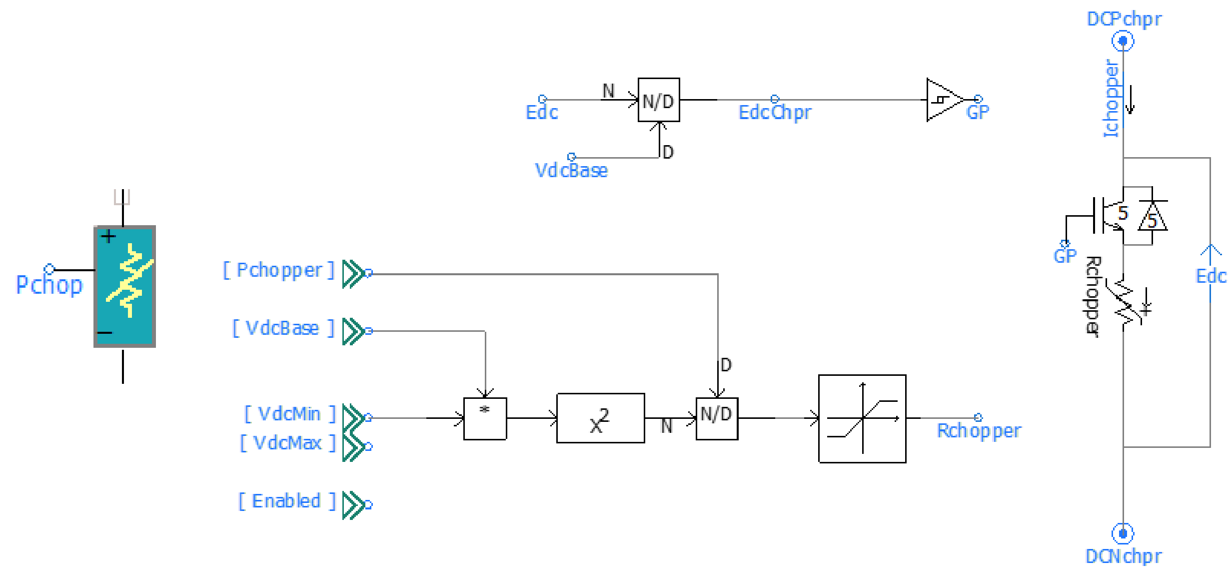


Figure 27: Machine side AC voltage controller

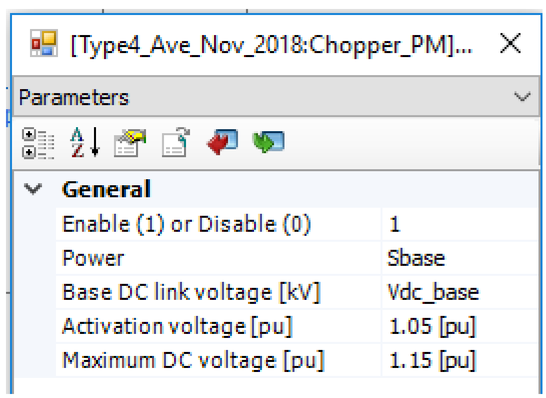
The decupled current controllers and the procedure to create the reference voltages for this controller is the same as the grid-side one.

4.1.3 DC-link Chopper

Further protection during fault condition is required to avoid overvoltage on the DC-link capacitor. This protection is provided by the DC-link Chopper which is IGBT-controlled resistance that dissipate overvoltage. A voltage hysteresis controller is used to issue the chopper firing pulses. The logic of the DC-link Chopper is illustrated in Figure 28.



(a) (b)

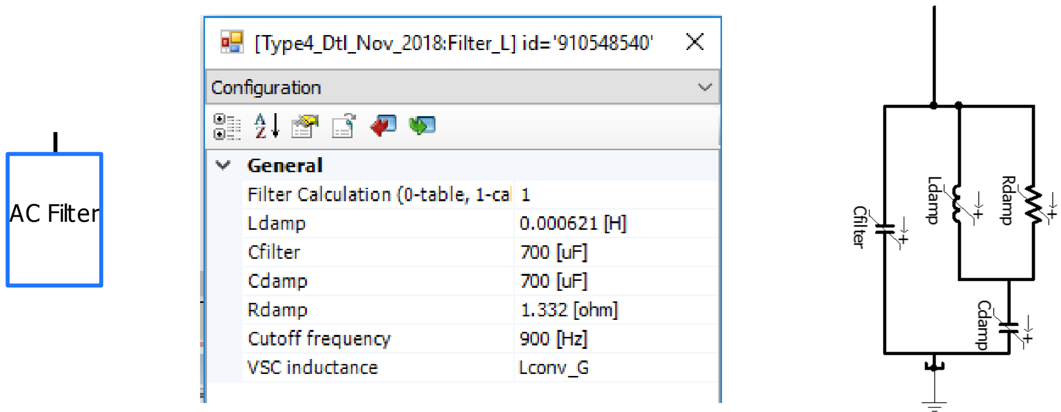


(c)

Figure 28: DC-link chopper (a) component, (b) electrical circuit and hysteresis controller(c) input parameters

4.1.4 Low Pass Filter

The power electronic converters generate a considerable amount of harmonics. A filter is used on the Ac side of the converters to minimize the impact of harmonics on the grid. The structure of the filter is represented in Figure 29. There are several filter topologies and methods suggested in the literature on how to calculate the filter parameters.



(a) (b) (c)

Figure 29: AC filter (a) component (b) parameters (c) circuit

The methodology used in this example to calculate the filter parameters is described as the following section.

4.1.5 Filter parameters calculation

According to [1], the switching frequency can be calculated as follows

$$f_{sw} = \frac{V_{DC}}{8 \times L_{inv} \times I_{rpp}} \text{, where} \quad (9)$$

I_{rpp} – the peak-to-peak amplitude of the ripple current, which can be estimated as 20% of peak-to-peak nominal current:

$$I_{maxAC} = I_{nomAC} \times \sqrt{2} \text{, where} \quad (10)$$

$$I_{nomAC} = \frac{P_{conv}}{\sqrt{3} \times V_{L-Lrms}} \quad (11)$$

For our system using (10) and (11) the peak-to-peak current will be

$$I_{nomAC} = \frac{2.14}{\sqrt{3} \times 0.69} = 1.79 \text{ kA}$$

$$I_{maxAC} = 1.79 \times \sqrt{2} = 2.54 \text{ kA}$$

The ripple current approximately

I_{rpp} = 0.2 * 2.54 = 0.508 kA

The switching frequency using (9)

$$f_{sw} = \frac{1.45}{8 \times 0.000106 \times 0.508} = 3369 \text{ Hz}$$

The carrier frequency as multiple of fundamental:

$$C_{freq} = \frac{f_{sw}}{f} \quad (12)$$

$$C_{freq} = \frac{3369}{50} = 67.38$$

A cutoff frequency of 200 Hz for the filter is used.

The filter capacitance needed to provide the cutoff frequency with the inductor (L) can be found as follows:

$$C_{filter} = \frac{1}{(2 \times \pi \times f_{cutoff})^2 \times L} \quad (13)$$

The filter capacitance for the system using (A5)

$$C_{filter} = \frac{1}{(2 \times \pi \times 200)^2 \times 0.000106} \times 10^6 = 5974\, uF$$

The damping circuit is needed to reduce or eliminate any possible ringing caused by the combination L and C_{filter}. The damping inductance takes the value of:

L_{damp} = 5*L_{VSC} (14)

L_{damp} = 5*0.000106=0.00053 H

The damping capacitance can be calculated:

$$C_{damp} = \frac{C_{filter}}{2} \quad (15)$$

$$C_{damp} = \frac{5974}{2} = 2987\ uF$$

The damping resistance can be calculated:

$$R_{damp} = \sqrt{\frac{L_{damp}}{C_{damp}}} \quad (16)$$

$$R_{damp} = \sqrt{\frac{0.00053}{0.002987}} = 0.4212\ \Omega$$

4.1.6 Scaling Component

Figure 30 shows the scaling component that represents an aggregated wind farm. In this example the wind farm has 100 units. The output current of the wind turbine is multiplied by the number of units (n = 100) and injected to the power system through current sources.

Also the scaling component should be considered when it comes to reactive power. The scaling component is modelled similar to a transmission line with one simulation time step (dt) delay. The equivalent capacitor (*C*) value can be calculated for this component in:

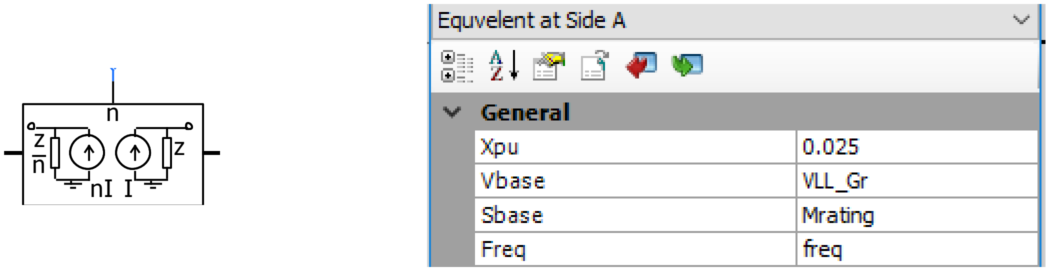
$$C = dt/Zc \quad (4)$$

where *dt*, and *Zc* are simulation time step and the equivalent surge impedance, respectively.

The equivalent surge impedance can be calculated as :

$$Zc = \sqrt{L/C} \quad (5)$$

To minimize the effect of the series inductor of the scaling component we can use part of leakage reactance of the connecting transformer or interconnected cables and transmission lines if there is any. A damping resistance may use in parallel to this component to damp numerical instability.



(a) (b)

Figure 30: Scaling component to aggregate wind farm (a) the component (b) the input parameters

5 Dynamic responses of the detailed and the average models

The dynamic behaviors of the detailed and average models are compared during two transient conditions. In the first transient the wind speed is varied slowly around its nominal speed to obtain lower and higher speed ratings. In the second transient a three phase to ground fault is incepted on the BusPOC for duration of 0.15sec.

5.1 Dynamics against wind speed variations

Figure 31 and Figure 32 show dynamic responses of the average and detailed models respectively when the speed of wind is changes over time. It can be seen that the dynamics of the average and detailed models are quite similar and close enough to use averaged model as a replacement of the detailed model. Also, total CPU Time for average model is 131.75 s while it is about 959.453s for detailed model. This indicates that, the average model is 7.28 times faster than the detailed model in terms of simulation time.

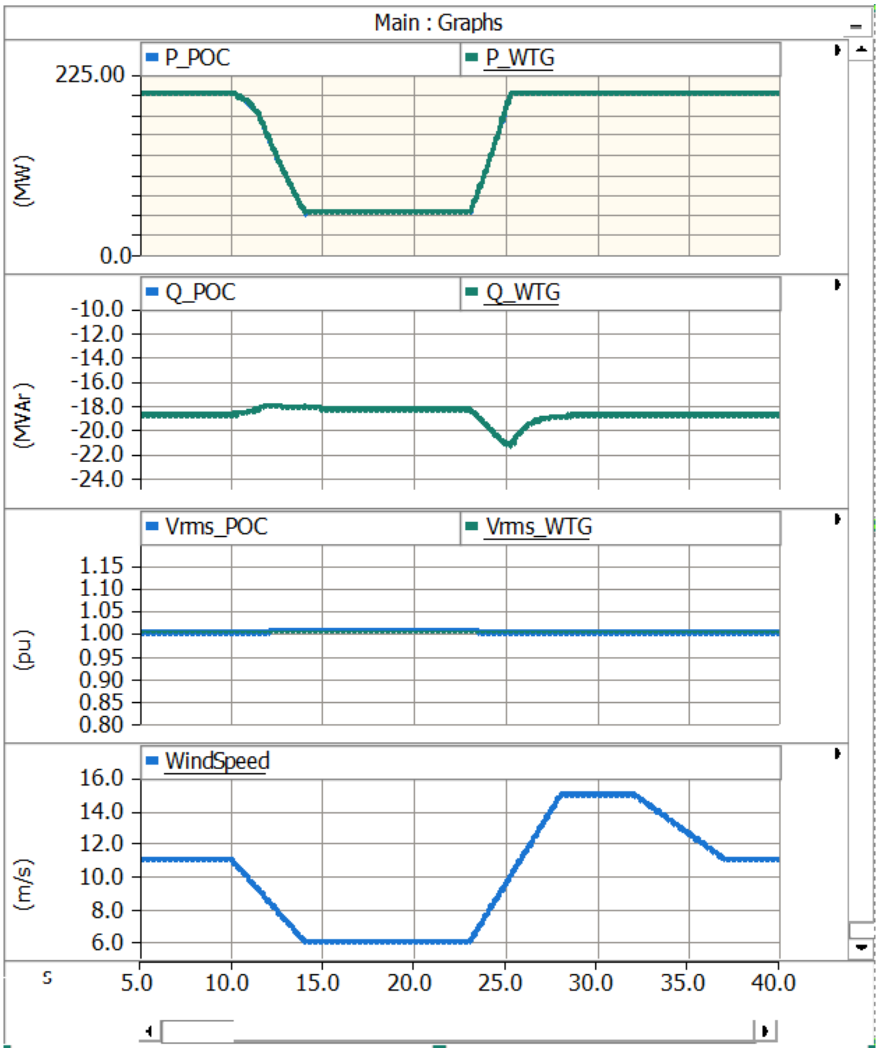


Figure 31: Dynamic responses of the average model during a change in a wide range of wind speed

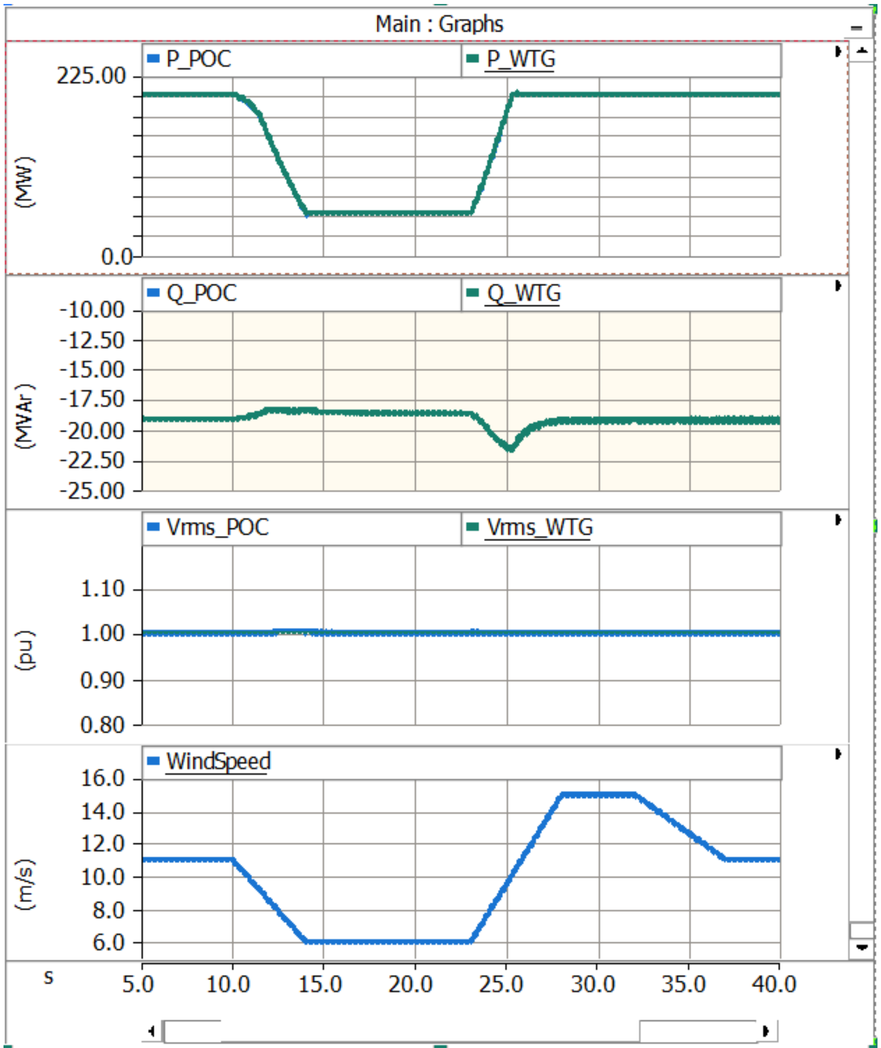


Figure 32: Dynamic responses of the detailed moel during a change in a wide range of wind speed

5.2 Dynamics against faulty condition

Figure 33 and Figure 34 show the dynamic responses of the average and detailed models during a three phase to ground fault on the BusPOC at 7sec respectively. The transients for the dc voltages, active and reactive powers and speed are quite similar. The wind speed is at its nominal value i.e. 10m/sec. as it is expected from previous simulation, the average model is 7 times faster than the detailed model in terms of simulation time.

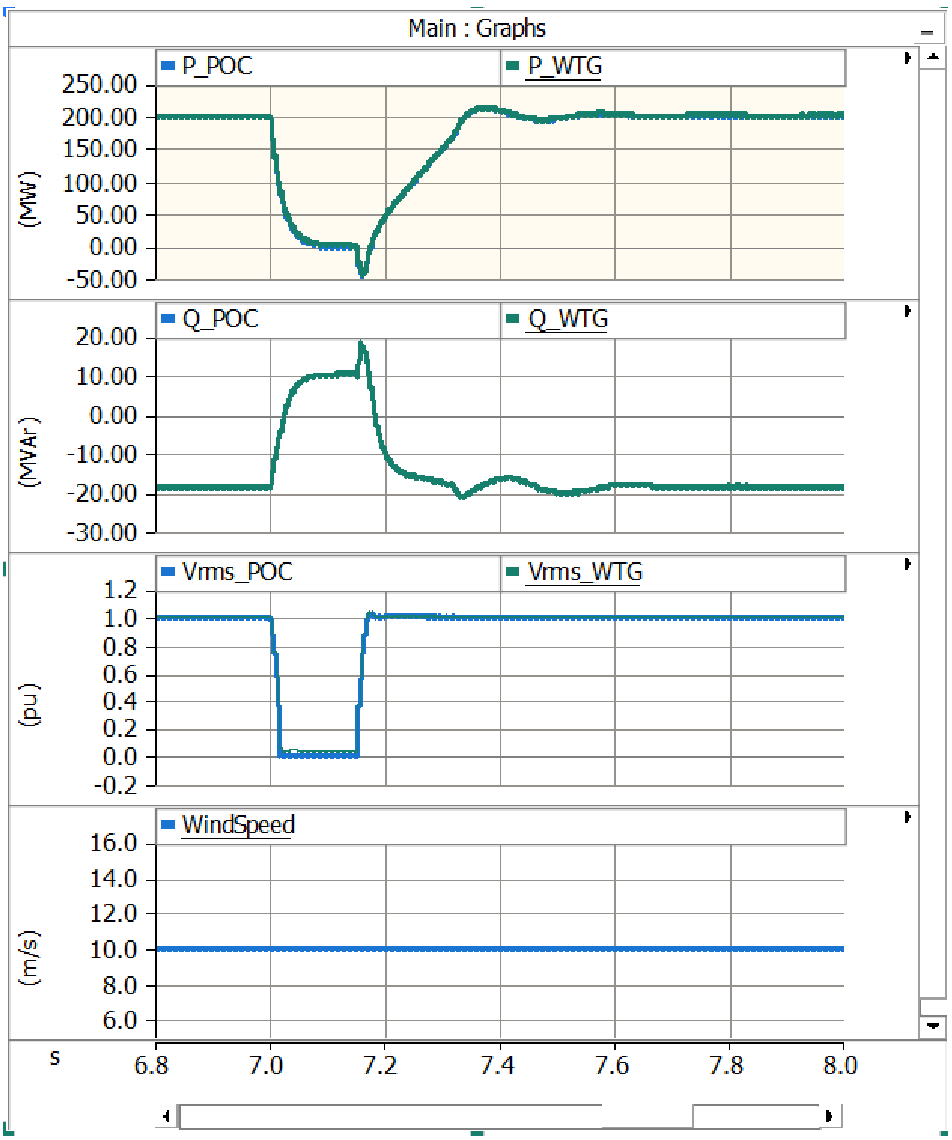


Figure 33: Dynamic responses of the average model for a fault on POC

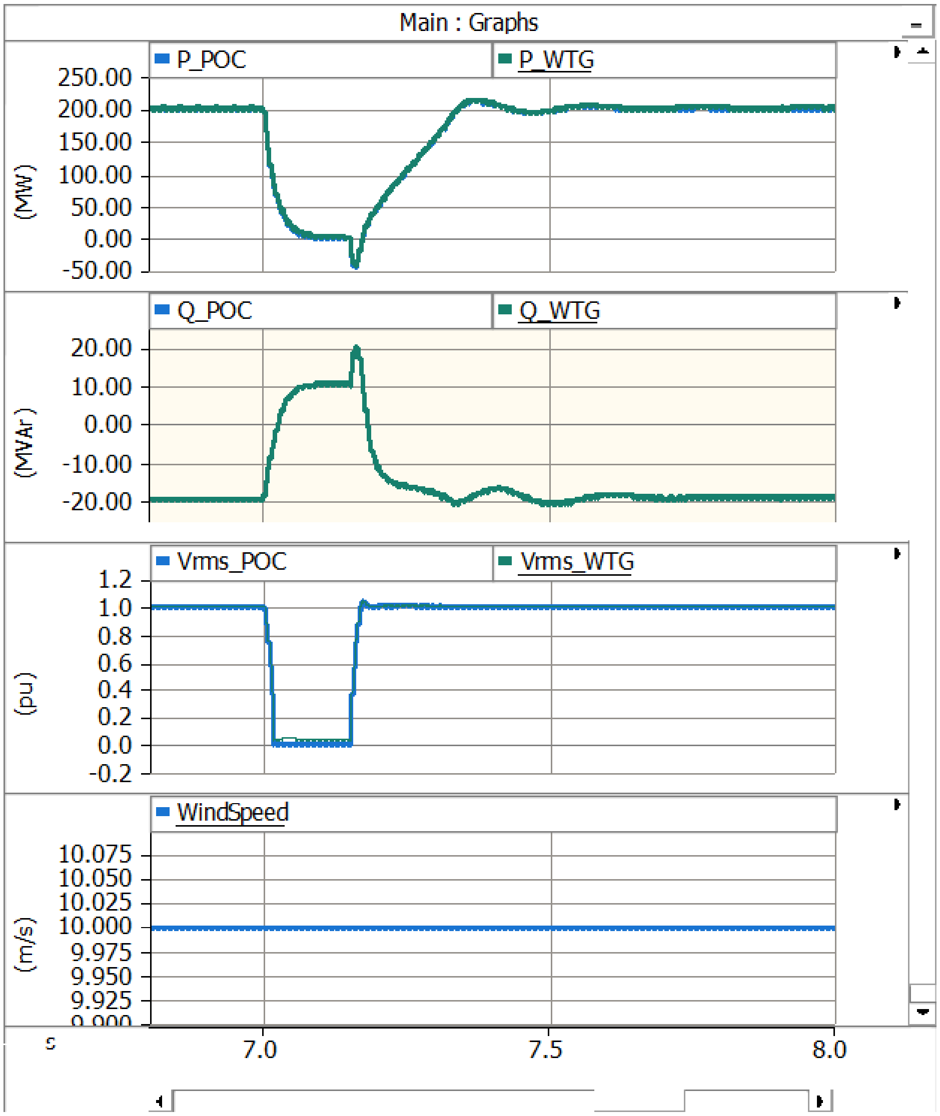


Figure 34: Dynamic responses of the detailed model for a fault on POC

6 References

[1] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998

[2] Kara Clark, Nicholas W. Miller, Juan J. Sanchez-Gasca, "Modeling of GE Wind Turbine-Generators for Grid Studies," Version 4.5, April 16, 2010