| Rev. | Date | Auth | Change / Comment | Checked | Date |
|---|---|---|---|---|---|
| A | 2012-05-08 | RamMi | First version of FPC Matlab simulation model (FPCSIM) description | PolRi | 23-05-23 |
| B | 2012-07-12 | RamMi | Added chapter 5 (Author´s notes) and Figures 2-4 updated | PolRi | 2012-07-12 |
| C | 2013-03-08 | PolRi | Complete revision of the text<br>Modified Fig. 2 and Table 1<br>Added Fig.4 and parameter tables 2-4 | | |
| | | | | | |

**Full-power converter**

# FPCSIM

## Simulation model description

# 1 Introduction

## 1.1 Purpose of this document

This document describes the available full-power converter simulation model for Matlab simulink (FPCSIM). FPCSIM consists of simulation model for the The Switch full-power converter (FPC) and permanent magnet generator (PMG) package based on Vacon NXP inverter modules.

## 1.2 Simulation model overview

FPCSIM is based on modularity indicating that the complete system model is divided into functionally and logically reasonable subsystems. Subsystems containing intellectual property are protected by auto-generating and compiling a corresponding C-coded S-function from the original block diagram model. Each subsystem can be individually parametrized using the mask parameters.

## 1.3 Model structure

The overall structure of the FPCSIM is shown in Fig. 1. FPCSIM describes the behavior of the wind turbine electrical drive train from the electromechanical input of the permanent magnet generator to the grid interface (i.e. LV/MV transformer). This part of the model can be parametrized for the needed power level. The model can be used to simulate the grid impact of the wind turbines with FPC in normal operation and in low-voltage ride-through (LVRT) situations. In LVRT situations the level of the DC intermediate circuit voltage is protected if necessary using dynamic electrical brake.

The model of the electrical drive train consists of detailed dynamic models for grid side filter, DC intermediate circuit, permanent magnet generator and the controls of the both converters. Mechanical drive train is not modeled. Optionally the LV/MV transformer and the medium voltage (MV) grid models can be included to the simulation model package. Both the grid and generator side power stages are modeled as voltage sources with modulation scheme depended output voltage capability and characteristics.

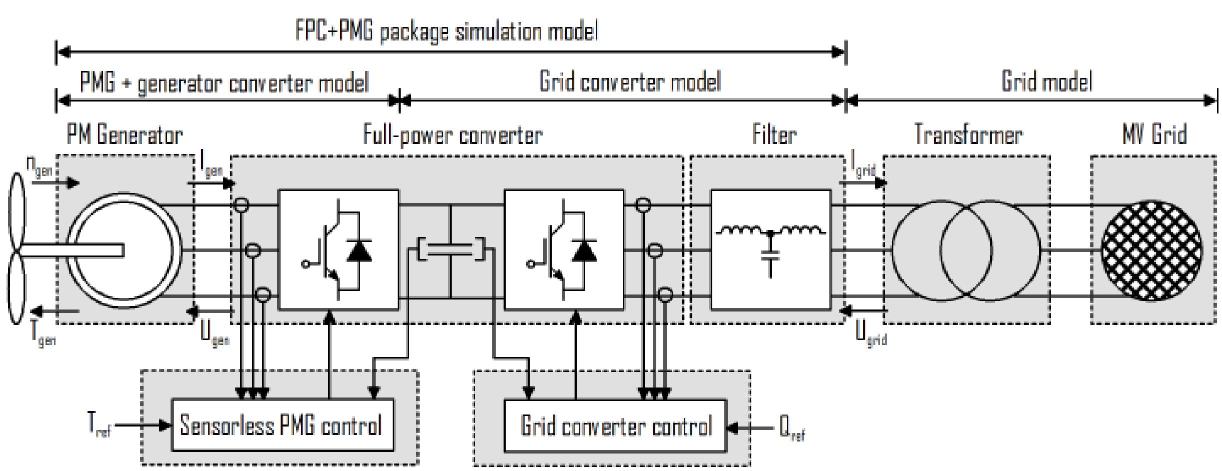



*Figure 1. Block diagram of the FPC-PMG package*

## 1.4 Full-power converter fundamentals

PM generator is connected to the power grid through a full-power converter. This configuration decouples the generator frequency from the power grid frequency. Therefore the electrical dynamic performance of the wind turbine with FPC seen by the power grid is completely dominated by the operation of the grid side converter and the electrical behavior on the generator side of the FPC is of no interest to the AC power system. Further, generator side operation is not needed for the converter to operate on reactive power on the grid-side. Control of active and reactive power is handled by fast, high bandwidth current regulators within the grid converter control. Fast current control allows that the power electronic stages of the converter can be greatly simplified for simulation of the power system dynamic performance. Therefore the power stages are represented with controllable voltage sources instead of actual power electronic switches.

## 1.5 Properties of simulation model

Simulation model is developed with Matlab/Simulink simulation software with following versions:

| | | |
|---|---|---|
| **MATLAB** | **Version 7.13** | **(R2011b)** |
| **Simulink** | **Version 7.8** | **(R2011b)** |
| Control System Toolbox | Version 9.2 | (R2011b) |
| Fixed-Point Toolbox | Version 3.4 | (R2011b) |
| MATLAB Coder | Version 2.1 | (R2011b) |
| **SimPowerSystems** | **Version 5.5** | **(R2011b)** |
| Simscape | Version 3.6 | (R2011b) |
| Simulink Coder | Version 8.1 | (R2011b) |

Only the highlighted modules are needed for running the simulation model. For the best possible compatibility of the model the usage of the same or newer software versions is recommended.

# 2 Simulation model interface signals

In *Figure 2* is shown the main view and contents of the FPCSIM model and *Figure 3* shows the contents of the “PMG-FPC Package” blocks.

*Table 1* lists all the available converter signals of the converter simulation model. The Switch converter simulation model (FPCSIM) have fixed amount of simulation modelling signals.

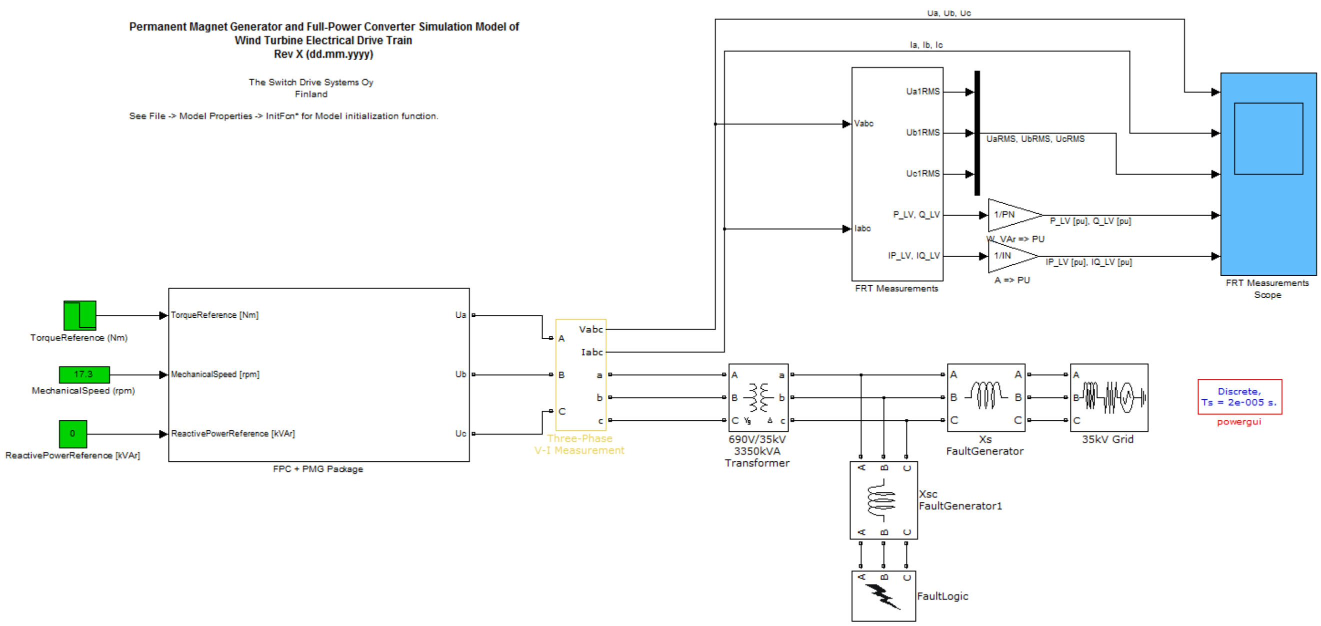



*Figure 2. Main view of the simulation model*

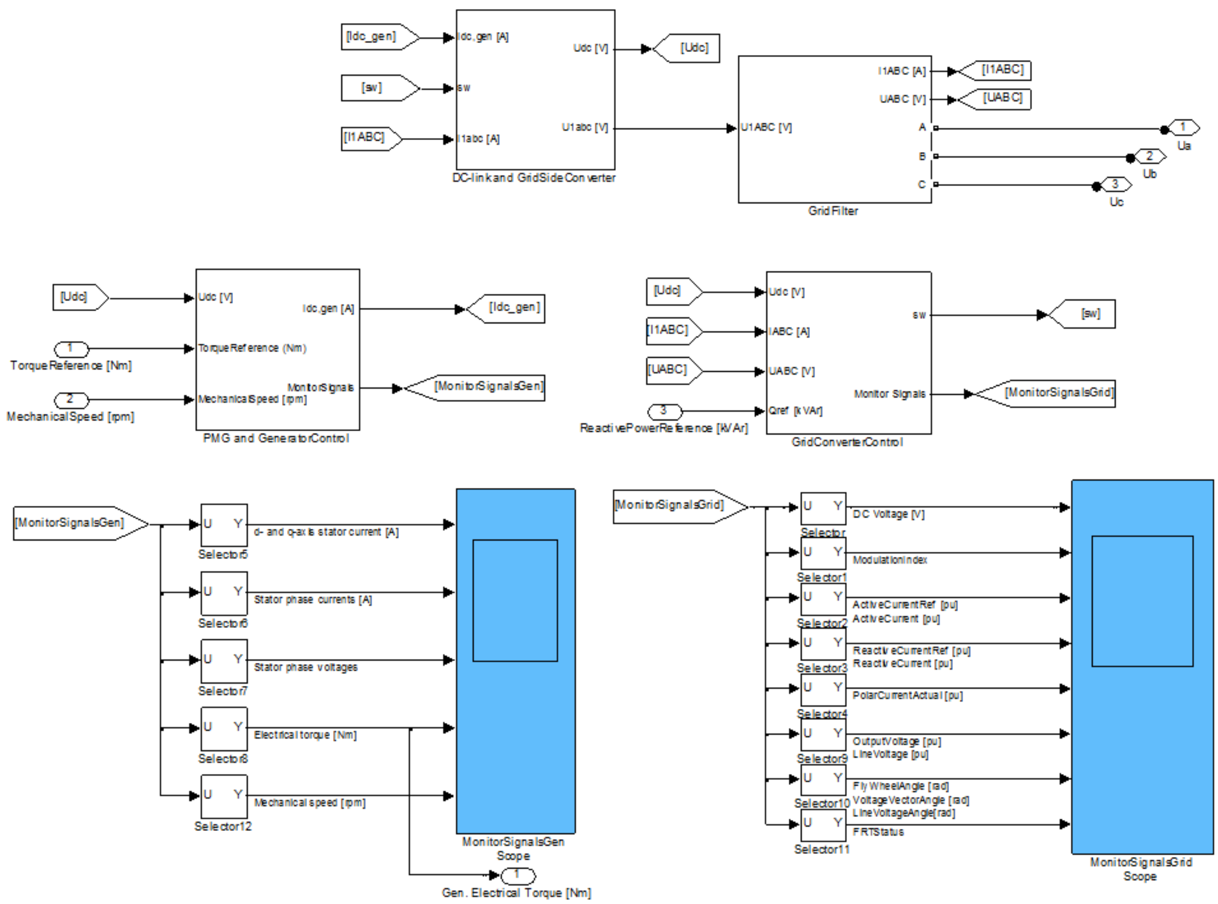



*Figure 3. Content of the “FPC+PMG Package” block*

*Table 1. Available converter signals of the simulation model*

| Variable # | Variable name | Signal description | Notes |
|---|---|---|---|
| Grid side variables | | | |
| 1 | Ua,Ub,Uc | Grid voltage | Instantaneous low voltage side grid phase voltages Ua, Ub, Uc in volts (model input) |
| 2 | ReactivePowerReference | Reactive power reference | External reactive power reference for grid converter in kVArs (model input) |
| 3 | Ia, Ib,Ic | Grid current | Instantaneous low voltage side grid phase currents Ia, Ib, Ic in amps (model output) |
| 4 | UaRMS,UbRMS,UcRMS | Grid RMS voltage | True RMS value of low voltage side grid voltage |
| 5 | P_LV, Q_LV | Positive sequence active power, reactive power | 3-phase PQ [P(pu) Q(pu)] evaluated at the fundamental frequency. Values are in per units respect to the turbine nominal power PN. |
| 6 | IP_LV, IQ_LV | Positive seq. active current, reactive current | Active and reactive current [IP(pu) IQ(pu)] evaluated at the fundamental frequency. Values are in per units respect to the turbine nominal current IN. |
| Generator side variables | | | |
| 1 | MechanicalSpeed | Mechanical speed | Generator mechanical speed in rpm (model input) |
| 2 | TorqueReference | Torque reference | Generator torque reference in Nm (model input) |
| Monitoring signals (grid converter) | | | |
| 1 | DC Voltage | MonitorSignalsGrid Scope | Full-power converter internal DC link voltage [V] |
| 2 | ModulationIndex | MonitorSignalsGrid Scope | Modulation index |
| 3 | ActiveCurrentRef<br>ActiveCurrent | MonitorSignalsGrid Scope | Reference and actual value of grid converter instantaneous active current [pu] |
| 4 | ReactiveCurrentRef<br>ReactiveCurrent | MonitorSignalsGrid Scope | Reference and actual value of grid converter instantaneous reactive current [pu] |
| 5 | PolarCurrentActual | MonitorSignalsGrid Scope | Magnitude of grid converter instantaneous current [pu] |
| 6 | OutputVoltage<br>LineVoltage | MonitorSignalsGrid Scope | Grid converter power module output voltage [pu]<br>Grid voltage measured by the grid converter at the capacitors of the LCL grid filter [pu] |
| 7 | FlyWheelAngle<br>VoltageVectorAngle<br>LineVoltageAngle | MonitorSignalsGrid Scope | Angle of grid converter PLL [rad]<br>Angle of instantaneous grid converter output voltage vector [rad]<br>Angle of instantaneous LineVoltage vector [rad] |
| 8 | FRTStatus | MonitorSignalsGrid Scope | Grid converter control FRT status word |
| Monitoring signals (generator converter) | | | |
| 1 | d- and q-axis stator current | MonitorSignalsGen Scope | Generator d and q axis stator current [A] |
| 2 | Stator phase currents | MonitorSignalsGen Scope | Generator stator phase currents Iabc [A] |
| 3 | Stator phase voltages | MonitorSignalsGen Scope | Generator stator phase voltages Uabc [V] |
| 4 | Electrical torque | MonitorSignalsGen Scope | Generator electrical torque estimated by the generator control [Nm] |
| 5 | Mechanical speed | MonitorSignalsGen Scope | Generator mechanical speed measured/estimated by the generator control [rpm] |

# 3 Basic operation with the simulation model

Unzip the model zip-file into desired destination folder. The zip-package contains three files:

| | |
|---|---|
| FPCSIM_XXX_RevYY.mdl | This is the main Simulink simulation model file |
| GridControl_sf.mexw32 | Object file of grid converter control s-function |
| PMG_GenControl_sf.mexw32 | Object file of PMG and generator control s-function |

Start Matlab and change the folder where you unzip the files as the working directory. Open the file FPCSIM_XXX_RevYY.mdl and the model consistency by clicking CTRL + d. If everything is in order there should not be any error or other messages in the Matlab command window.

Set the wind turbine operation point with TorqueReference (Nm) and MechanicalSpeed (rpm) sources. If the FPCSIM model is used as part of the mechanical drive train model, TorqueReference (Nm) and MechanicalSpeed (rpm) sources can be removed and the signal lines connected to the corresponding outputs of the external mechanical drive train model and wind turbine controller as shown in block diagram in Fig. 4. External reactive power reference can be given to the ReactivePowerReference in kVArs.

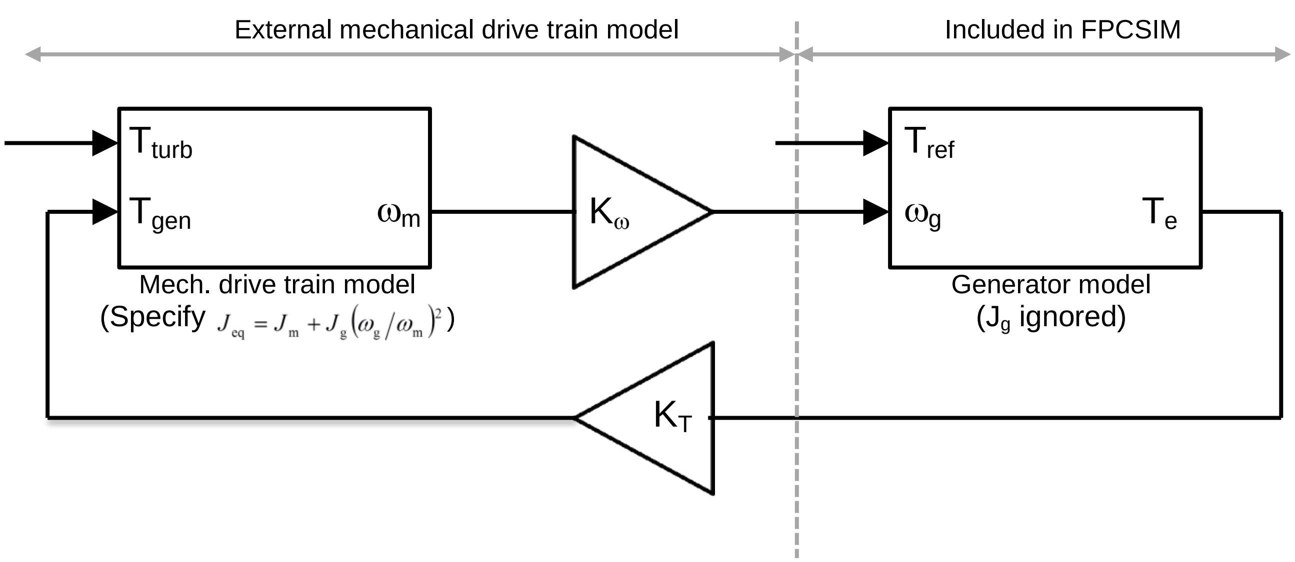



*Figure 4. Block diagram of connecting an external model of the mechanical drive train with the FPCSIM generator model.*

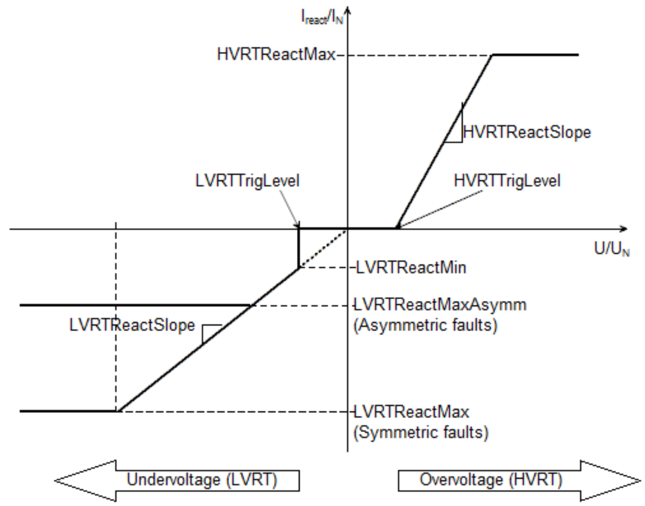
# 4 Parameters

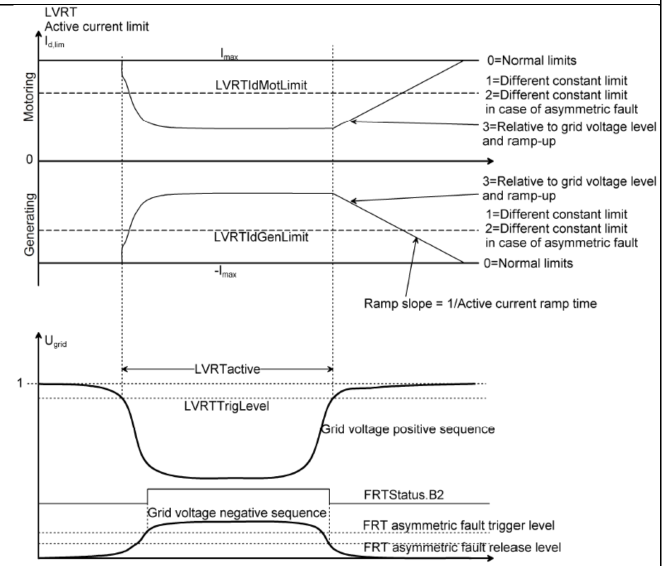
The Switch converter simulation model consists of simple block inputs for parametrization. Definitions and descriptions of the parameters of FPCSIM simulation model are given in Tables 2-4.

*Table 2. Grid converter control parameters*

| Parameter | Unit | Default value | Description |
|---|---|---|---|
| ***Basic parameters*** | | | |
| Converter nominal values<br>UN<br>IN<br>fN | <br>[V]<br>[A]<br>[Hz] | <br>690<br>-<br>50 | Grid converter nominal values<br>Nominal phase-to-phase voltage<br>Nominal phase current<br>Nominal grid frequency<br><br>Nominal values specify the base values of the per unit system of the grid converter control. Therefore user should not normally need to change them. |
| Maximum current limit, Imax | [A] | - | Maximum grid converter current |
| Modulator type | | 1 | ASIC modulator = 0<br>SW-modulator = 1 |
| Switching frequency, fsw | [Hz] | 3600 | Switching frequency of the grid converter power stage. Defines the sample times of the discrete-time control.<br><br>Note: Models with compiled s-function models of control do not support adjustable switching frequency parameter. Therefore fsw should not be changed by the user. |
| Line filter inductance, Lf | [H] | | Line filter inductance between the reactive power control point and the voltage used for grid converter control orientation. |
| Line filter capacitance, Cf | [F] | 612e-6 | Line filter capacitance (equivalent Y-connection value) |
| Simulation initial values<br>theta0<br>Udc0 | <br>[rad]<br>[V] | <br>$-\pi/2$<br>1050 | Simulator initial values (@ $t_{sim}$ = 0) for grid control.<br>Initial angle of grid voltage (transformer LV side)<br>Initial DC link voltage of full-power converter |
| ***DC voltage control parameters*** | | | |
| DC voltage reference | [V] | 1053 | Reference of DC link voltage |
| DC voltage control limits<br>Udcrefmin<br>Udcrefmax | <br>[V]<br>[V] | <br>976<br>1100 | <br>Minimum value of DC voltage reference<br>Maximum value of DC voltage reference |
| DC voltage control gain and integration time<br>Kp_udc<br>Ti_udc | <br>[pu]<br>[s] | <br>6.1<br>0.05 | |
| DC voltage control filter, Tf_udc | [s] | 0.7e-3 | Filter time constant of DC voltage controller error signal |

| **Parameter** | **Unit** | **Default value** | **Description** |
|---|---|---|---|
| ***Current control parameters*** | | | |
| Active current controller gain and integration time<br>Kp_id<br>Ti_id | <br><br>[pu]<br>[s] | <br><br>0.4<br>1.5e-3 | |
| Modulation index limit | | 1.0 | Limit of maximum modulation index reference for modulation.<br>(1 = 100%, limit of linear modulation range) |
| Reactive current controller gain and integration time<br>Kp_iq<br>Ti_iq | <br><br>[pu]<br>[s] | <br><br>0.4<br>3e-3 | |
| Voltage margin | | 0.97 | Reference of maximum steady-state modulation index. (1 = 100%, limit of linear modulation range) |
| Auto reactive current reference limit | [pu] | 0.1 | Maximum limit of inductive reactive current for voltage margin controller. |
| ***Phase-locked loop parameters*** | | | |
| PLL gain and integration time<br>Kp_PLL<br>Ti_PLL | <br>[1/s]<br>[s] | <br>46.875<br>0.05 | |
| ***FRT parameters*** | | | |
| FRT mode trigger level<br>FRT normal dip level<br>FRT low dip level<br>FRT model off level<br>FRT clearance time<br>FRT blind time | [pu]<br>[pu]<br>[pu]<br>[pu]<br>[s]<br>[s] | 0.6<br>0.5<br>0.25<br>0.8<br>0.04<br>1.0 | These parameters control the operation of the internal Phase-Locked Loop (PLL) used in synchronous coordinate current control during the grid voltage fault.<br><br>NOTE! External operation of the grid converter such as the grid voltage support during the voltage dip is NOT set by these parameters. |
| FRT asymmetric fault trigger level<br><br><br>FRT asymmetric fault release level | [pu]<br><br><br>[pu] | 0.08<br><br><br>0.04 | Trigger level (rising edge) for negative sequence voltage amplitude above which the grid fault is categorized as asymmetric fault.<br>Reset level (falling edge) for negative sequence voltage amplitude under which the asymmetric grid fault is considered to be ended.<br><br>FRTStatus.B2 indicates the state of above conditions. |
| Line voltage feedback gap<br><br>Line voltage feedback gain | [pu]<br><br>[pu] | 0.1<br><br>1.0 | Voltage difference needed to activate line voltage feedback (feedforward) terms of current controllers.<br>Gain of line voltage feedback (feedforward) terms. |
| Negative sequence voltage filter cutoff frequency | [Hz] | 20 | Cut-off frequency (-3dB) of low-pass filter of negative sequence voltage amplitude. |

<table>
<tr><th>Parameter</th><th>Unit</th><th>Default value</th><th>Description</th></tr>
<tr><td colspan="4">LVRT/HVRT parameters</td></tr>
<tr><td>LVRTTrigLevel<br>LVRTReactMin<br>LVRTReactSlope<br>LVRTReactMax<br>LVRTReactMaxAsymm<br><br>HVRTTrigLevel<br>HVRTReactSlope<br>HVRTReactMax</td><td>[pu]<br>[pu]<br><br>[pu]<br>[pu]<br><br>[pu]<br><br>[pu]</td><td>0.9<br>0<br>2<br>1.0<br>1.0<br><br>1.1<br>0<br>0</td><td>Parameters define the dynamic grid voltage support by injection of reactive current as specified in the characteristics shown below.

</td></tr>
<tr><td>LVRT Generating side active current limiting mode:<br>0 = No special limiting (use normal limits)<br>1 = Different constant limit (LVRTIdGenLimit)<br>2 = Different constant limit in case of asymmetric fault (LVRTIdGenLimit)<br>3 = Relative to grid voltage level and ramp up (LVRTIdRampTime)<br><br>LVRT Motoring side active current limiting mode:<br>0 = No special limiting (use normal limits)<br>1 = Different constant limit (LVRTIdMotLimit)<br>2 = Different constant limit in case of asymmetric fault (LVRTIdMotLimit)<br>3 = Relative to grid voltage level and ramp up (LVRTIdRampTime)</td><td></td><td></td><td></td></tr>
</table>

| **Parameter** | **Unit** | **Default value** | **Description** |
|---|---|---|---|
| ***LVRT/HVRT parameters*** | | | |
| LVRT Id limits[1]:<br>LVRTIdGenLimit<br>LVRTIdMotLimit<br><br>Active current ramp time after LVRT (LVRTIdRampTime) | <br>[pu]<br>[pu]<br><br><br>[s] | <br>-0.9<br>0.1<br><br><br>0.5 |  |
| ***Options parameters*** | | | |
| Enable filter reactive power compensation | | TRUE | Grid filter reactive power compensation disabled/enabled. |
| Enable grid voltage orientation (D7 coordinates) | | TRUE | FALSE = converter voltage orientation is used<br>TRUE = grid voltage orientation is used |
| Use OutputVoltage as FRT voltage | | FALSE | FALSE = measured grid voltage @ filter capacitors is used as voltage signal for FRT functions<br>TRUE = converter output voltage (= power module terminal voltage) is used as voltage signal for FRT functions |
| Enable negative sequence current control | | FALSE | Disable/enable control which adjusts the negative sequence current to zero resulting in to more symmetrical and balanced phase currents |

[1] In FPCSIM versions dated before 24.10.2012 the corresponding parameters are named as LVRT Id limits, [LVRTIdMinLimit (pu), LVRTIdMaxLimit (pu)]. In addition, only the modes 0 and 1 are available for motoring side and modes 0 and 2 for generating side. Mode 1 for motoring and mode 2 for generating are enabled by selecting *Enable LVRTIdMinMaxLimits* from Options tab of the Grid converter control block.

*Table 3. PMG and generator control parameters*

| **Parameter** | **Unit** | **Default value** | **Description** |
|---|---|---|---|
| ***Basic parameters*** | | | |
| Nominal voltage Un | [V] | | Nominal generator phase-to-phase terminal voltage |
| Nominal current In | [A] | | Nominal generator phase current |
| Nominal frequency and pole pair number<br>fn<br>p | <br><br>[Hz] | | <br><br>Nominal generator stator frequency<br>Number of pole pairs |
| Back-EMF E | [V] | | Back-EMF induced by the permanent magnet flux at nominal speed |
| Stator inductances<br>Lsd<br>Lsq | <br>[mH]<br>[mH] | | <br>Stator direct axis inductance<br>Stator quadrature axis inductance |
| Stator resistance Rs | [mΩ] | | Stator resistance |
| ***Sensorless parameters*** | | | |
| Estimated stator inductances<br>Ld_est<br>Lq_est | <br>[mH]<br>[mH] | | <br>Stator direct axis inductance estimate used in control<br>Stator quadrature axis inductance estimate used in control |
| Estimated stator resistance Rs_est | [mΩ] | | Stator resistance estimate used in control |
| Estimated Back-EMF E_est | [V] | | Estimated Back-EMF used in control |
| Voltage model correction<br>Kp<br>Ti | <br>[pu]<br>[s] | <br>0.4 | <br>Gain and integration time constant of voltage model correction |
| Speed estimator parameters<br>Kp<br>Ti | <br>[pu]<br>[s] | <br>1.4 | <br>Gain and integration time constant of generator speed estimator (PLL) |
| Speed estimate filter time Tf_wgest | [s] | 0.01 | Time constant of speed estimate filtering |
| ***Control parameters*** | | | |
| Direct axis current controller<br>Kp_id<br>Ti_id | <br>[pu]<br>[s] | | <br>Gain and integration time constant of d-axis current PI-controller |
| Quadrature axis current controller<br>Kp_iq<br>Ti_iq | <br>[pu]<br>[s] | | <br>Gain and integration time constant of q-axis current PI-controller |
| Switching frequency, fsw | [Hz] | 2400 | Switching frequency of the grid converter power stage. Defines the sample times of the discrete-time control. |
| Torque reference limit | [pu] | 1.5 | Maximum value for torque reference. Applies for both negative and positive reference. |
| Voltage margin for FW-control | | 0.97 | Stator voltage reference for field weakening control.<br>1= Max output voltage @ linear modulation range limit |

| Parameter | Unit | Default value | Description |
|---|---|---|---|
| ***Initial values*** | | | |
| Generator initial values | | | Simulation initial values (@ $t_{sim}$ = 0) for PMG and generator control. |
| theta0 | [rad] | 0 | Initial angle of generator rotor d-axis |
| n0 | [rpm] | | Initial speed of generator rotor |
| udc0 | [V] | 1050 | Initial DC link voltage of full-power converter |
| ***Options*** | | | |
| Use sensorless control | | TRUE | FALSE = rotor speed/position is measured with speed/position sensor<br>TRUE = estimated rotor speed/position is used in control |
| Enable MTPA algorithm | | | FALSE = Maximum Torque Per Ampere operation disabled (only possibility if Lsd = Lsq)<br>TRUE = Maximum Torque Per Ampere operation enabled and reluctance torque is utilized (Lsd ≠ Lsq required) |

*Table 4. DC-link and Dynamic Brake parameters*

| Parameter | Unit | Default value | Description |
|---|---|---|---|
| DC-link capacitance Cdc | [F] | | Total capacitance of converter DC-link |
| Initial DC-link voltage Udc0 | [V] | 1050 | Initial voltage of DC link |
| FPC no-load losses | [W] | | Total no-load losses of the full-power converter |
| Brake resistor, Rbrake | [Ω] | | Equivalent 1-phase resistance of Dynamic braking resistors |
| DBU activation level | [V] | 1120 | Activation voltage level of Dynamic Braking Unit |
| DBU deactivation level | [V] | 1090 | Deactivation voltage level of Dynamic Braking Unit |
| DBU switching frequency | [Hz] | 3600 | Switching frequency of the Dynamic Braking Unit. Defines the sample time of the discrete-time control. |

# 5 Notes and remarks

Remarks regarding the usage of simulation model and verification of FRT measurements:

**FPCSIM must be used only to simulate the grid impact of the wind turbines with FPC in normal operation as well as in low-voltage ride-through (LVRT) events. The usage for estimating converter or drive-train efficiency, harmonics etc. is highly forbidden. The Switch is not responsible other usage of the FPCSIM. The Switch held rights to change contents of the simulation model.**

- Remaining voltage levels (positive and negative sequences) during the fault have enormous significance to the amount of reactive current injected by the grid converter. Correct voltage levels as well as phase shift should be therefore repeated in the simulation as accurately as possible to get the correct simulation response.

- The lower the remaining voltage level during the fault the more accurately repeated voltages compared to the measurement is needed. Grid converter control includes certain nonlinear control features, which are directly dependent on the voltage levels having therefore a remarkable influence on the control performance and response. For example transformer saturation effect, which takes normally place in field tests with test container and real transformer, has a dramatic influence on control behavior when distorting the instantaneous voltage waveforms.

- Transformer and grid model and parameter provided with the simulation model package are only illustrative and not presenting the real experimental setup. User of the simulation model must provide the correct model/parameters for the transformer and grid and possible transmission lines or cables.

- FRT measurements and signals calculated in the provided model package are also only illustrative. Simulator user must incorporate and use the same signal processing algorithms which have been used with experiments.

- The Switch will not take the responsibility of modeling the mechanical drive train not included in the scope of our delivery (turbine rotor, main shaft, gearbox, etc.) because we do not have detailed information about the mechanical system.

- Because the basic version of the PMG model does not include the model of mechanical drive train system (= rotating rotor) the inertia is ignored and the mechanical speed is given as an input signal to specify the operation point in terms of generator rotational speed. Generator control system does not require that information directly, but it uses an internal estimate for that. However, the electromagnetic model of the “true“ PMG requires the rotational speed as an input variable.

- If the generator speed is really wanted to be a controlled variable in the simulation model it has to be then also modeled by introducing an external dynamic model of the rotor system to the model. Model of rotor dynamics can be easily incorporated into to existing simulation by the end user. There is no limitation by the delivered simulation model for that.