PSCAD DYNAMIC MODELS FOR PV INVERTER AND POWER PLANT CONTROLLER HEMK v 1001

Power Electronics
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Revision Table						
Revision	Date			Author	Reviewed	Approved
1	Jan	31	2019	A. Garcia	G. Fernandez	V. Abad

Document Revision History			
Revision	**Date**	**Author/Reviewed/Approved**	**Description**
1	31/01/2019	AGL/GFQ/VA	Initial Version

Model Revision History			
Revision	**Date**	**Author/Reviewed/Approved**	**Description**
1.00	01/25/2018	AGL/GFQ/JC	Initial Version
1.01	03/22/2018	AGL/GFQ/JC	PSCAD v4.6.2 Migration and LVRT modes added.
1.02	04/10/2018	AGL/GFQ/JC	Protection bug solved
1.03	05/02/2018	AGL/GFQ/JC	LVRT output improvement
09.00	09/28/2018	AGL/GFQ/VA	Model Update
09.01	10/02/2018	AGL/GFQ/VA	Q-V curve and LVRT output P ramp added.
09.02	10/10/2018	AGL/GFQ/VA	LVRT algorithm improvement
09.03	08/11/2018	AGL/GFQ/VA	LVRT algorithm improvement
10.00	16/11/2018	AGL/GFQ/VA	Control algorithm improvement
10.00a	07/01/2019	AGL/GFQ/VA	HVRT algorithm updated
10.01	31/01/2019	AGL/GFQ/VA	PPC Q-V Curve Close Loop algorithm added.

TABLE OF CONTENTS

1 AIM

The present document has the following main objectives:

- Explain how to use the inverter model: Descriptions, diagram blocks, parameterization and model validation.
- Explain how to use the PPC model: Diagram blocks, descriptions, parameterization and model validation.

!

The model can be adjusted to represent any single HEMK converter extracted from the Power Electronics' brochure and an aggregated model of the whole plant.
All the parameters are completely adjustable (VRATED, FRATED, PRATED, etc.).
However, the user must take special care when changing the rated power of the converter: the LCL filter should be adjusted.

!

The static and dynamic parameters of the model that is delivered correspond to the configuration used to generate the simulations shown in the user manual. Therefore, all the settings must be reviewed and adjusted by the user according to the requirements of the plant for which the model will be used, as well as what is required by the current applicable grid code and other requirements of network operators to which there is place.

!

The model has been adjusted to 4.82 us time step, this value should not be changed in order to avoid internal issues. In case it is necessary to change the default time step, consult PE.

2 MODEL OVERVIEW

The PSCAD Solar Inverter model is a dynamic simulation model of HEMK built by Power Electronics. This document outlines the modelling of the Inverter model in PSCAD EMTDC environment, i.e. a time-based simulation software.

The PSCAD Solar inverter model is delivered as a compressed file which is comprised of:

Table 1: Deliverable file main components

File name	Type	Location
*.pscx	PSCAD v 4.6.2 file	Working project folder
*.lib	Library object file compiled using Intel Fortran XE 13.0.0.089.	Working project folder

The present document explains the Power Electronics' inverter and *Power Plant Controller* (PPC) model in PSCAD. This model has been split in the following main parts:

- **Converter Model ['PE_GEN']:** includes all the inverter's hardware main components. It consists in a three-level topology inverter controlled from the "PE_CONT".
- **Control Model ['PE_CONT']:** includes the main control algorithms of the real inverter model with frequency and voltage protections.
- **Power Plant Controller Model ['PE_PPC']:** includes all the main control algorithms of the Power Plant Controller.

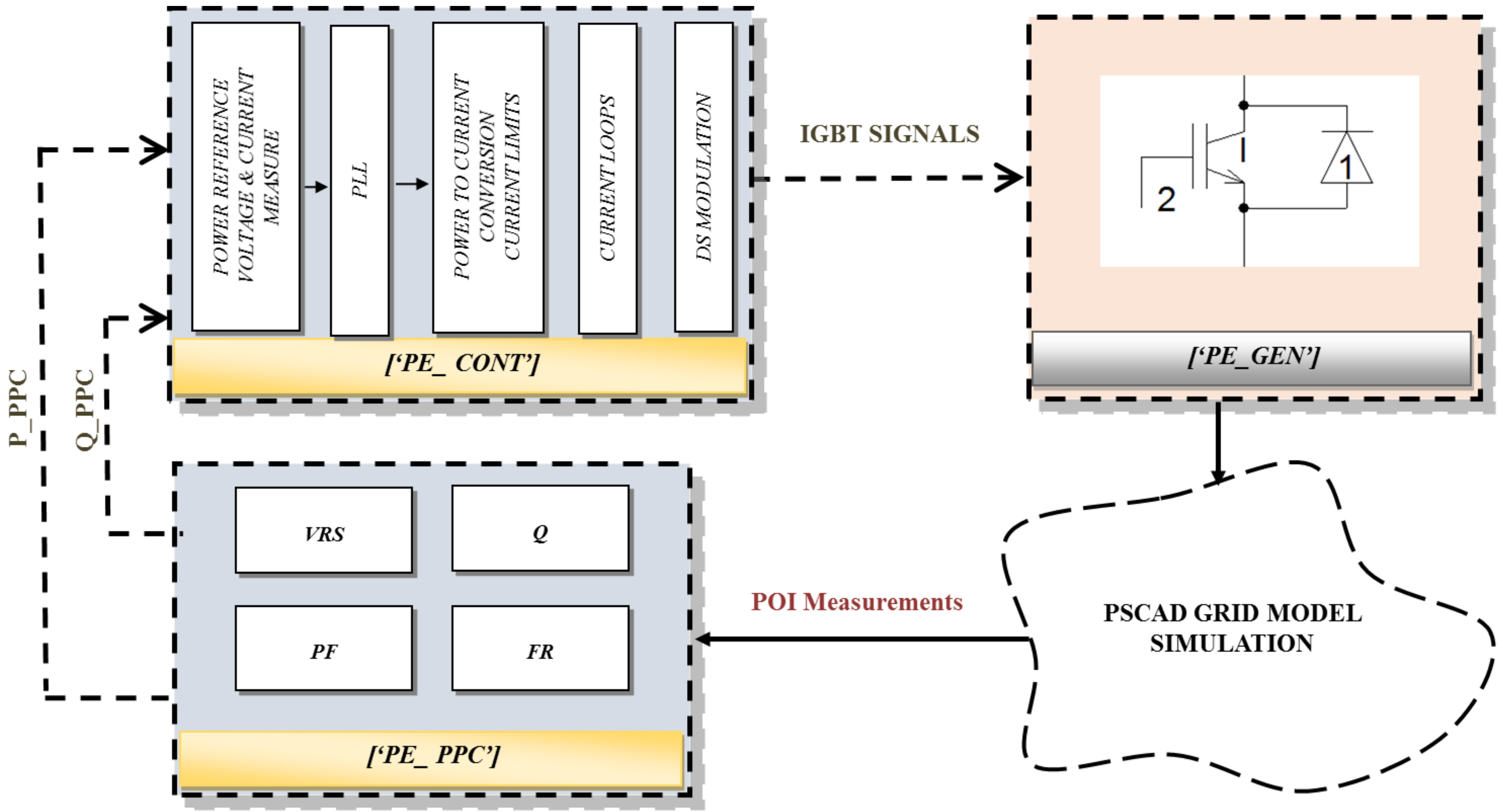


Figure 1. PV inverter and PPC model overview

3 INVERTER AND PPC MODEL

3.1 Model Parametrization

All the power converters have, as main goal, the control of the grid currents. Therefore, in order to use the converter model, the "*PE_GEN*" block must be linked with the desired grid model.

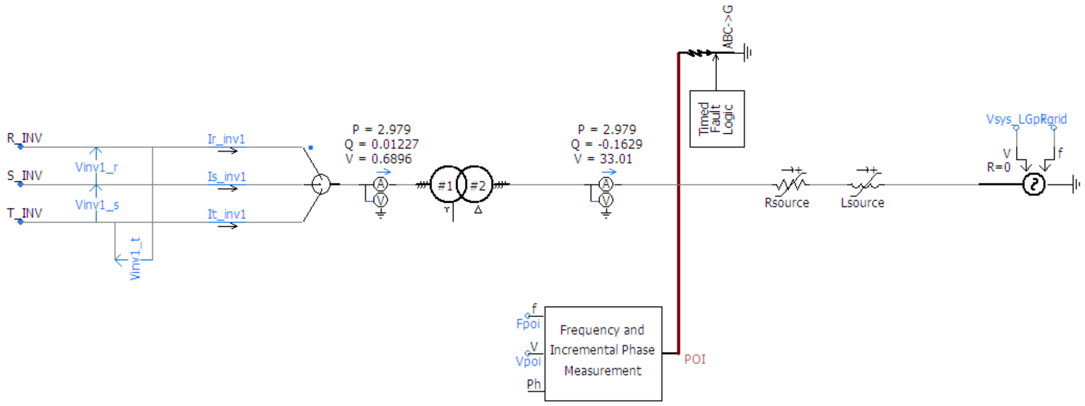


Figure 2: Grid model overview

Within the example model attached with this manual, a generic grid model has been used; the user can control the main magnitudes of a grid such as voltage, frequency, short circuit ratio (SCR), etc.

The settings shown in Table 2, Table 3, Table 4 and Table 5 are the default values of the model.

3.2 Dynamic Models

The dynamic behaviour of the PE inverter and PPC can be modelled with the following set of models:

- **Generator model ['PE_GEN']:** The converter hardware: Made up with "*NPC three level topology*", "*DC source*", "*LCL filter*" and "*AC contactors*". It injects active and reactive current into the grid in response to control commands ('PE_CONT').

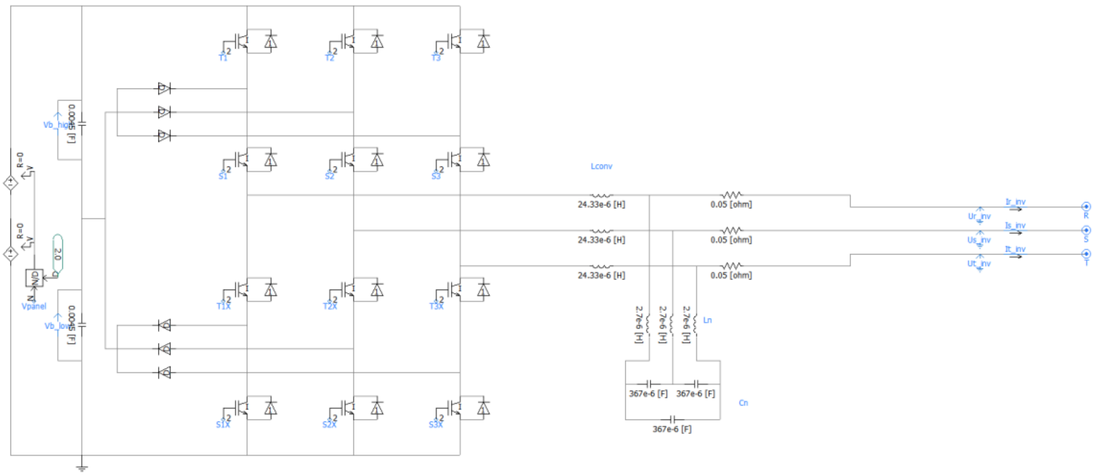
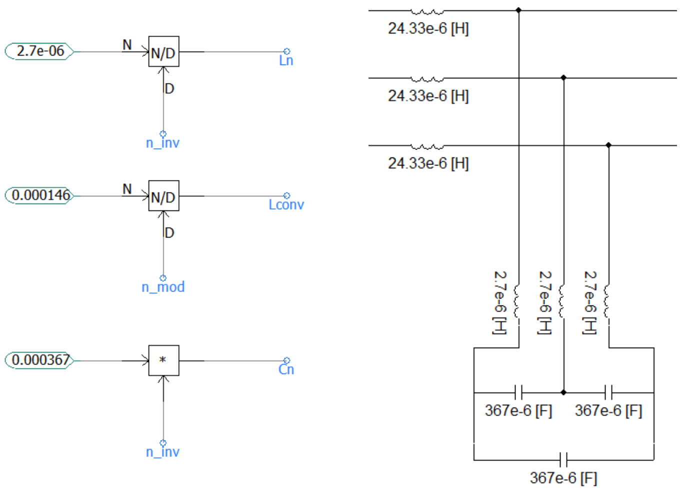


Figure 3: *"PE_GEN"* converter model overview

- LLC Filter should be adjust depending of the plant rated power.
  The parametrization of the LLC is calculated automatically according to the number of Inverters/ modules, that make up the aggregated plant, the calculated values must be introduced in the "PE_GEN" LLC.



- **Control model [‘PE_CONT’]:** It measures the voltage and current at converter terminals, implements the PLL and current limits algorithms, computes the current loops and sends the IBGT firing signals to the converter model (‘PE_GEN’).

  The model also implements the following protections that can be enabled or disabled:

  - 5 high voltage protections
  - 1 high phase instantaneous protection
  - 5 low voltage protections
  - 5 high frequency protections
  - 5 low frequency protections

- **Power Plant Controller model [‘PE_PPC’]:** It measures several magnitudes at POI (*Point of Interconnection*), solves the algorithms (VRS, PF, Q, Q-V, FR) and sends the power commands to the *Control Model* [‘PE_CONT’].

- **Grid model:**

Name	Value	Description
SCR	5	Test Bench Short Circuit Ratio
Vpu	1.0	Grid Voltage [p.u.]
Fpu	1.0	Grid Frequency [p.u.]
X_R_ratio	10	Test Bench X/R ratio.

3.2.1 Generator Model [*'PE_GEN'*] Parametrization

Table 2: "PE_GEN" parameters

Name	Value	Description
V	0.69	Inverter Rated Voltage [kV]
V1	33.0	Grid Rated Voltage [kV]
Sinv	3.3	Rated Power [MVA]
Fn	50	Grid Rated Frequency [Hz]
Vpanel	1.5	DC voltage [kV]
inv_bat	0	inv_bat =1 Bidirectional, =0 Unidirectional.
Splant	3.3	Plant Rated Power [MVA]
n_mod	6.0	Plant number of modules (n_mod = n_inv * 6)
n_inv	1.0	Plant number of inverters.
P_inv	1.0	Inverter P Command [p.u.]
Q_inv	0.0	Inverter Q Command [p.u.]
EN_PPC	0	Enable PPC: =0 (Disable); =1 (Enable).
Vref_poi	1.0	POI Voltage reference [p.u.]
Qref_poi	1.0	POI Q reference [p.u.]
PF_poi	1.0	POI PF reference
Pref_sys	1.0	POI P reference [p.u.]

3.2.2 Control Mode [‘PE_CONT’] Parametrization

Table 3: “PE_CONT” parameters (I)

Name	Value	Description
L_lcl	24.66e-6	L_lcl: Lumped primary inductor value (H)
R_lcl	0.001	R_lcl: Lumped primary resistor value (Ohm)
Q_max	1.00	Q_max: Maximum Q limit [p.u.] (>0)
Q_min	-1.00	Q_min: Minimum Q limit [p.u.] (<0)
s_lim	1.00	s_lim: Apparent power limit [p.u.]
Plim	1.00	Plim: Active power limit [p.u.]
Is_lim	1.00	Is_lim: I apparent limit [p.u.]
PQpriority	1	Pqpriority =1 (P Priority); =0 (Q Priority)
Ramp_up_P	2.00	Ramp_up P: It implements the id ramp-up [p.u./s]
Ramp_down_P	2.00	Ramp_down P: It implements the id ramp-down [p.u./s]
Ramp_up_P_lvrt	50.00	Ramp_up_P_lvrt: It implements the id ramp-up during LVRT recovery [p.u./s]
Ramp_up_Q	4.00	Ramp_up Q: It implements the iq ramp-up [p.u./s]
Ramp_down_Q	4.00	Ramp_down Q: It implements the iq ramp-down [p.u./s]
LVRT_mode	0	LVRT_mode: =0 (K.dV, P=0); =1 (Sprev+K.dV, Ppriority); =2 (Sprev+K.dV, Qpriority)
Vth_lvrt	0.85	Vth_lvrt: V lvrt threshold [p.u.]
K_{LVRT}	2.0	K_{LVRT}: Gain for $K \cdot \Delta U$ in LVRT
Hyst_lvrt	0.05	Hyst: Hyst for LVRT output [p.u.]
Vset_lvrt	0.85	Voltage set for LVRT [p.u.]
Vth_hvrt	2.00	Vth_hvrt: V hvrt threshold [p.u.]
K_{HVRT}	2.0	K_{HVRT}: Gain for $K \cdot \Delta U$ in HVRT
Hyst_hvrt	0.05	Hyst for HVRT output [p.u.]
Vset_hvrt	1.2	Voltage set for HVRT [p.u.]
En_protec	0	En_protec: =1 (enable protections); =0 (disable protections)

Table 4: “PE_CONT” parameters (II)

Name	Value	Description
vh1	1.30	vh1 [p.u.]: vh1 threshold
vh2	1.28	vh2 [p.u.]: vh2 threshold
vh3	1.20	vh3 [p.u.]: vh3 threshold
vh4	1.10	vh4 [p.u.]: vh4 threshold
vh5	1.10	vh5 [p.u.]: vh5 threshold
vhi	1.50	vhi [p.u.]: vhi Instantaneous Threshold
vl1	0.00	vl1 [p.u.]: vl1 threshold
vl2	0.30	vl2 [p.u.]: vl2 threshold
vl3	0.50	vl3 [p.u.]: vl3 threshold
vl4	0.80	vl4 [p.u.]: vl4 threshold
vl5	0.80	vl5 [p.u.]: vl5 threshold
t_vh1	0.06	t_vh1 [s]: trip time vh1
t_vh2	0.20	t_vh2 [s]: trip time vh2
t_vh3	1.00	t_vh3 [s]: trip time vh3
t_vh4	9999	t_vh4 [s]: trip time vh4
t_vh5	9999	t_vh5 [s]: trip time vh5
t_vhi	0.001	t_vhi [s]: Instantaneous trip time vhi
t_vl1	1.00	t_vl1 [s]: trip time vl1
t_vl2	10.00	t_vl2 [s]: trip time vl2
t_vl3	21.00	t_vl3 [s]: trip time vl3
t_vl4	9999	t_vl4 [s]: trip time vl4
t_vl5	9999	t_vl5 [s]: trip time vl5
fh1	54.00	fh1 [Hz]: fh1 threshold
fh2	53.00	fh2 [Hz]: fh2 threshold
fh3	52.50	fh3 [Hz]: fh3 threshold
fh4	52.00	fh4 [Hz]: fh4 threshold
fh5	51.50	fh5 [Hz]: fh5 threshold
fl1	45.00	fl1 [Hz]: fl1 threshold
fl2	45.80	fl2 [Hz]: fl2 threshold
fl3	46.80	fl3 [Hz]: fl3 threshold
fl4	48.00	fl4 [Hz]: fl4 threshold
fl5	48.60	fl5 [Hz]: fl5 threshold
t_fh1	0.01	t_fh1 [s]: trip time fh1
t_fh2	160	t_fh2 [s]: trip time vh2
t_fh3	1000	t_fh3 [s]: trip time vh3
t_fh4	1800	t_fh4 [s]: trip time vh4
t_fh5	9999	t_fh5 [s]: trip time vh5
t_fl1	0.01	t_fl1 [s]: trip time vl1
t_fl2	160	t_fl2 [s]: trip time vl2
t_fl3	1000	t_fl3 [s]: trip time vl3
t_fl4	1800	t_fl4 [s]: trip time vl4
t_fl5	9999	t_fl5 [s]: trip time vl5

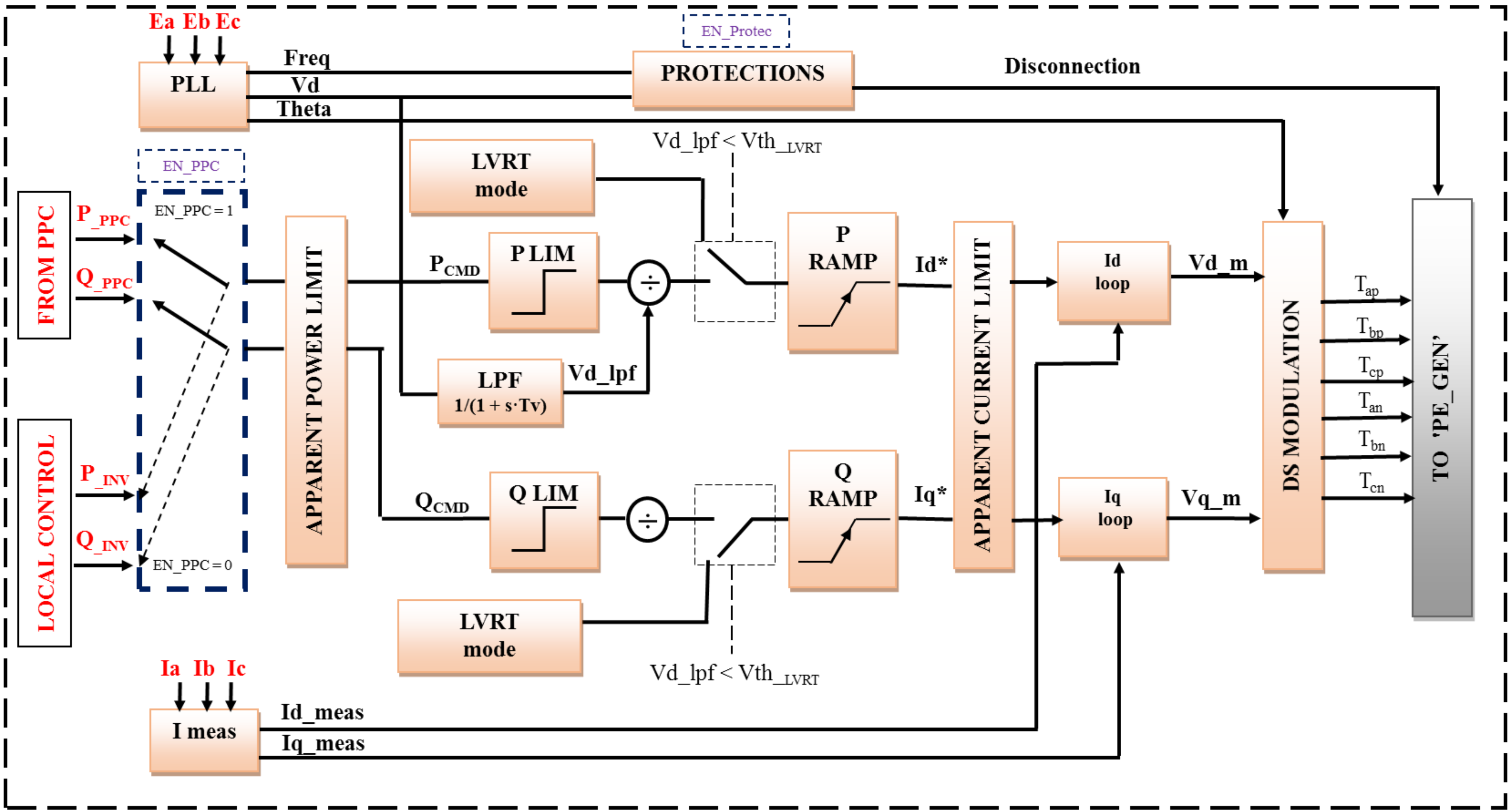


Figure 4: "PE_CONT" control mode

3.2.3 Power Plant Controller Model ('PE_PPC')

The Power Electronics "*Power Plant Controller*" is the device required to control several magnitudes at POI (*Point of Interconnection*).

The implemented model has the following functionalities:

- **POI Voltage Control (V_{CTRL}):** This control tries to help the grid to control the voltage at POI by injecting reactive power (capacitive => ↑V_{POI}, inductive => ↓V_{POI}). This control is done through a PI controller whose gains should be set depending on the grid characteristics (short circuit ratio) in order to achieve the desired control times.
- **POI Reactive Power Control (Q_{CTRL}):** A close loop control of the reactive power at POI (it has no dependence with the measured active power at POI). This control is done through a PI controller whose gains should be set depending on the grid characteristics (short circuit ratio) in order to achieve the desired control times.
- **POI Power Factor Control (PF_{CTRL}):** A close loop control of the measured power factor. This control is done through a PI controller whose gains should be set depending on the grid characteristics (short circuit ratio) in order to achieve the desired control times.
- **POI Q-V Curve Control (Q-V_{CTRL}):** A open/close loop control of reactive power at POI.

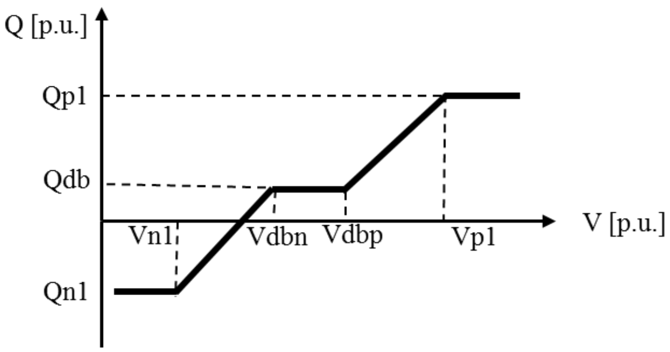


Figure 5: POI Q-V Curve control

- **POI Frequency Control (F_{CTRL}):** This control helps the grid to attenuate the frequency oscillations at POI. In order to do this, the P-f profile should be adjusted. The FR control mode can be set to rated active power or to instantaneous active power.

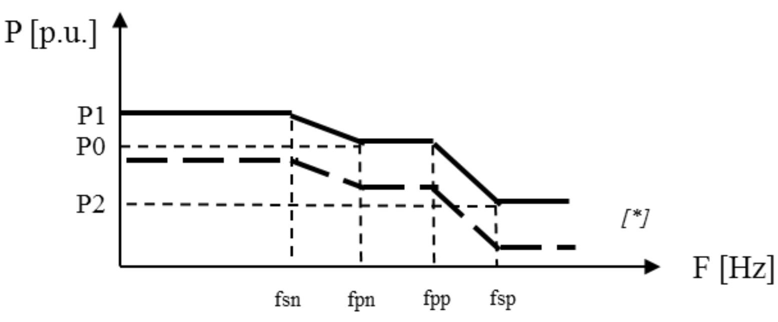
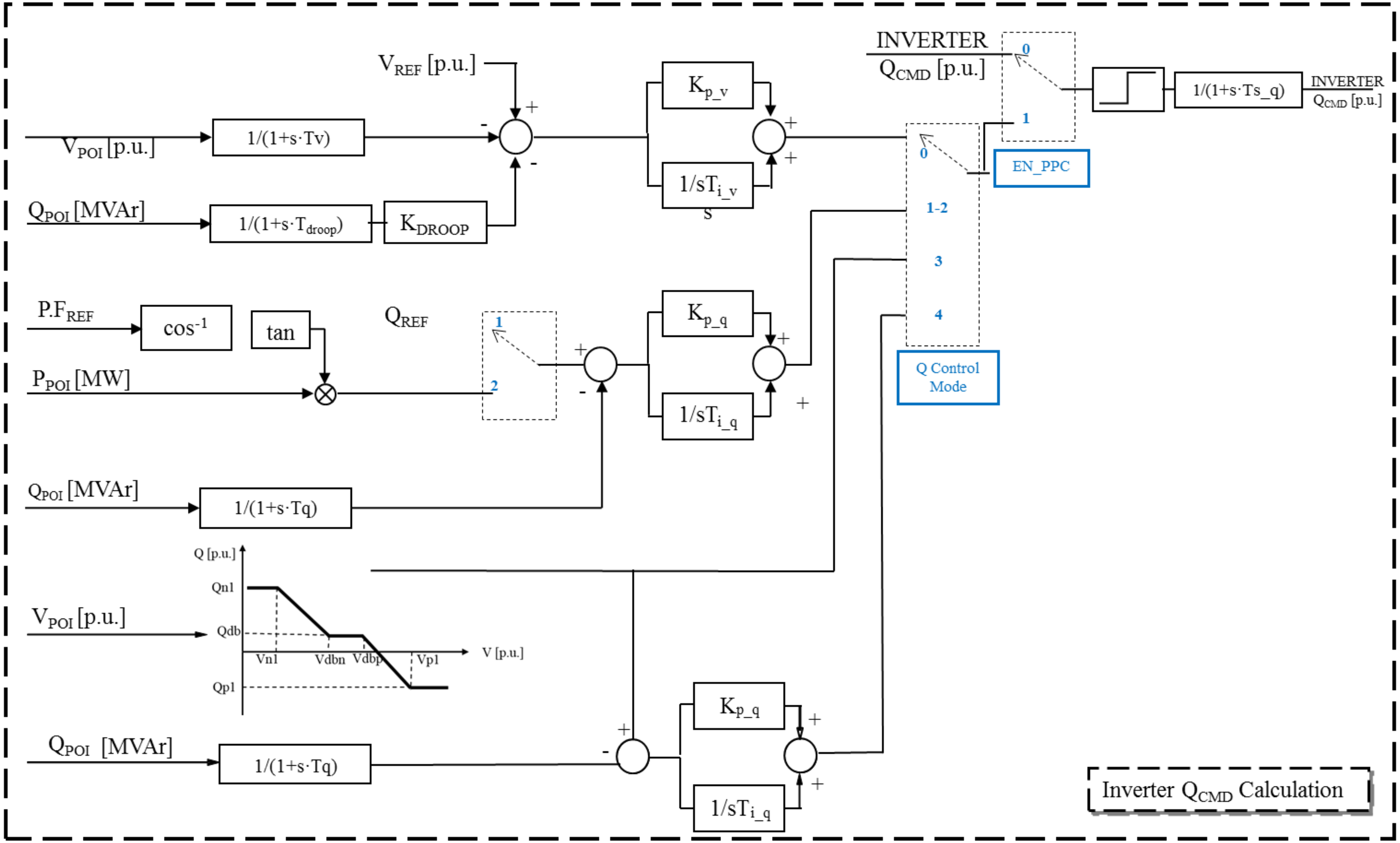


Figure 6: POI frequency control


VREF [p.u.]
VPOI [p.u.]
1/(1+s·Tv)
QPOI [MVAr]
1/(1+s·Tdroop)
KDROOP
Kp_v
1/sTi_v
INVERTER
QCMD [p.u.]
0
1
EN_PPC
1/(1+s·Ts_q)
INVERTER
QCMD [p.u.]
0
1-2
3
4
Q Control
Mode
P.FREF
cos-1
tan
QREF
PPOI [MW]
1
2
Kp_q
1/sTi_q
QPOI [MVAr]
1/(1+s·Tq)
Q [p.u.]
Qn1
Qdb
Qp1
Vn1
Vdbn
Vdbp
Vp1
V [p.u.]
VPOI [p.u.]
QPOI [MVAr]
1/(1+s·Tq)
Kp_q
1/sTi_q
Inverter QCMD Calculation

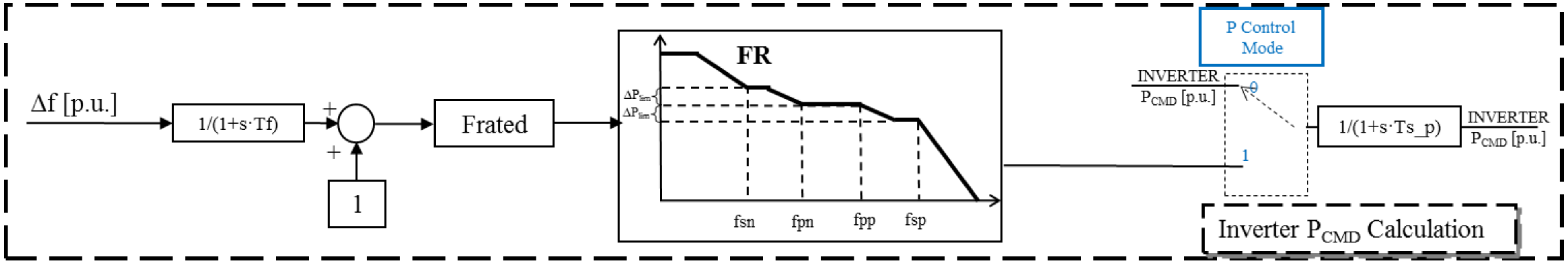


Figure 7. PE_PPC diagram block

3.2.4 PPC Model ('PE_PPC') Parametrization

Table 5: "PE_PPC" parameters

Name	Value	Description
Pcm	1	P Control Mode: 0 = (Disable FR); 1 = (Enable FR)
Fn	50	Fn: Rated frequency [Hz]
FRmode	1	FR Control mode: = 0 (P rated) = 1 (P meas)
fpp	51	fpp [Hz]: positive freq. for primary control
fpn	48	fpn [Hz]: negative freq. for primary control
fsp	55	fsp [Hz]: positive freq. for secondary control
fsn	45	fsn [Hz]: negative freq. for secondary control
slope_pp	5	slope_pp [%]: rate change in positive primary control
slope_sp	5	slope_sp [%]: rate change in positive secondary control
slope_pn	5	slope_pn [%]: rate change in negative primary control
slope_sn	5	slope_sn [%]: rate change in negative secondary control
dPlim	1.0	dPlim [pu]: ±dP limit in primary control
P_lim	1.0	P_lim: Active power limit [p.u.]
Qcm	0	Q Control Mode: = 0 (Voltage Ctrl); = 1 (Q Ctrl); = 2 (PF Ctrl) = 3 (Q-V curve open loop) = 4 (Q-V curve close loop)
Tf	0.2	Tf [s]: Delay in F measurement
Kp_v	0.05	Kp_v: Proportional gain for PPC Voltage Control
Ti_v	0.2	Ti_v: Integral gain for PPC Voltage Control
Vsat	0.9	Vsat: Saturation for LVRT
Vsat_hvrt	1.2	Vsat_hvrt: Saturation for HVRT
Tv	0.02	Tv: Delay in V measurement
Kdroop	0.00	Kdroop: Gain for the voltage droop
Tdroop	0.10	Tdroop: Delay in Qdroop measurement [s]
Kp_q	0.1	Kp_v: Proportional gain for PPC Q Control
Ti_q	0.2	Ti_v: Integral gain for PPC Q Control
Qmx	1.00	Qmx: Maximum Q to inverter [p.u.] (>0)
Qmn	-1.00	Qmn: Minimum Q to inverter [p.u.] (<0)
Tq	0.02	Tv: Delay in Q measurement
Vn1	0.9	Vn1: X axis Coordinate 1 for Q-V curve [p.u.]
Vdbn	0.95	Vdbn: X axis Coordinate 2 deadband negative for Q-V Curve [p.u.] (>Vn1)
Vdbp	1.05	Vdbp: X axis Coordinate 3 deadband positive for Q-V Curve [p.u.] (>= Vdbn)
Vp1	1.1	Vp1: X axis Coordinate 4 for Q-V Curve [p.u.] (>Vdbp)
Qn1	- 0.5	Qn1: Y axis Coordinate 1 for Q-V Curve [p.u.]
Qdb	0.0	Qdb: Y axis Coordinate 2-3 for Q-V Curve [p.u.] (>Qn1)
Qp1	0.5	Qp1: Y axis Coordinate 4 for Q-V Curve [p.u.] (>Qdb)
Ts_p	0.10	Ts_p: P command sending delay to inverter
Ts_q	0.10	Ts_q: Q command sending delay to inverter

4 RUNNING THE MODEL

The control parts of the PE converter SW have been embedded in the PSCAD model.

In order to keep private information, attached with the document has been included an Object Library with the embedded code.

To run the model, it is mandatory follow the next steps:

1. Open the PSCAD file “*.pscx”.
2. Copy the library file “*.lib” in the same directory where the PSCAD file is located.
3. Back in PSCAD, link the library files. To do so, go to the menu “Project/General Settings/Link” and, under ‘Additional Static Library’, place there the path to the library file.
4. Build and Run.

5 MODEL VALIDATION

5.1 Test Bench Overview

This report includes several tests in order to show the successful response of the inverter and PPC models.

The test bench (figure below) consists on a voltage source against the inverter. A typical 6% transformer has been included in order to simulate the real behaviour of the inverter in a real system.

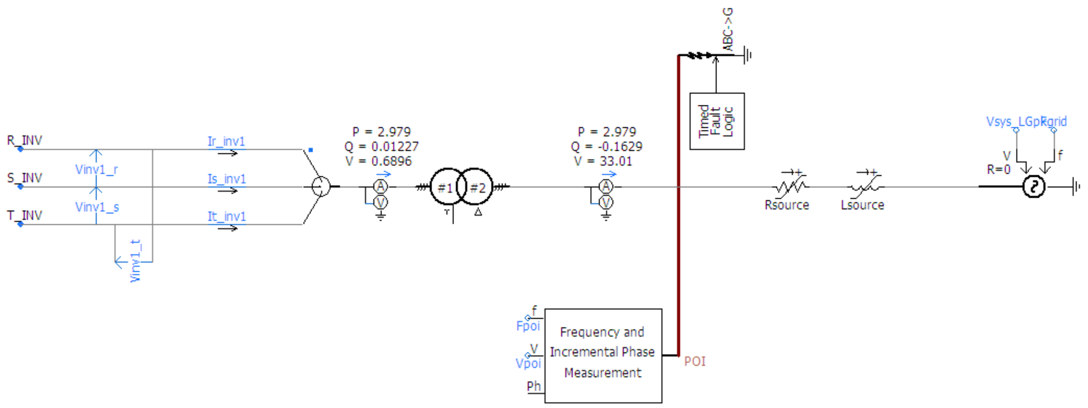


Figure 8: Test bench overview

“IDEAL SOURCE” SHORT CIRCUIT POWER:

The model response of the inverter (especially when the PPC is enabled) depends on the *Short Circuit Ratio (SCR)* of the grid (and consequently it depends on the Thevenin equivalent impedance).

$$SCR = \frac{Ssc}{Pn}$$

- SCR = Short Circuit Ratio
- Ssc = Short circuit power of the grid
- Pn = Rated power of the aggregated inverter

5.2 Inverter Model Results (Validation)

The following results show the inverter model responses **without PPC**. Notice that in order to completely remove the PPC commands, the EN_PPC of the model must be set to 0 as follows:

Figure 9: PPC disabled

5.2.1 Test 1: Inverter P Commands

Figures below show the model response for several commands of active power.

Table 6: P commands unidirectional converter-inverter model response

Time [s]	P command [p.u.]	Machine output [MW]
[1,2]	0.2	0.66
[2, 3]	0.4	1.32
[3, 4]	0.6	1.98
[4, 5]	0.8	2.64
[5, 6]	1.0	2.29
[6, 7]	0.8	2.64
[7, 8]	0.6	1.98

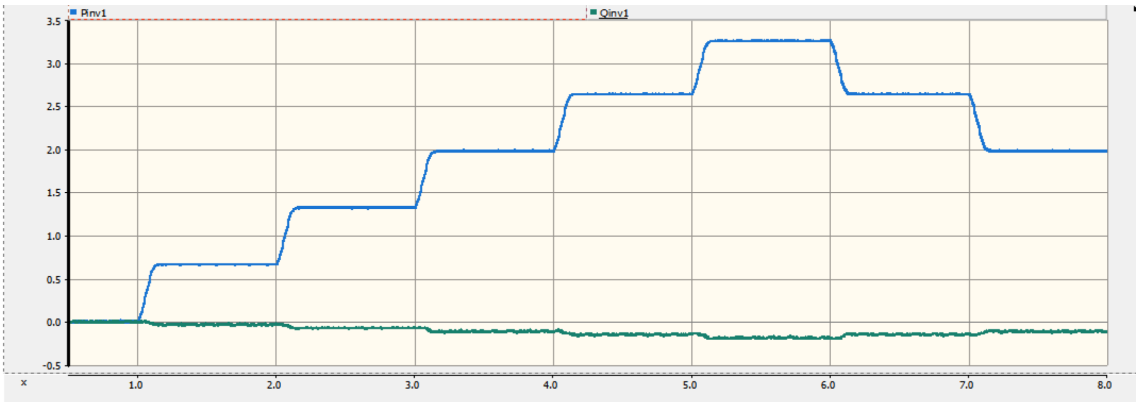


Figure 10: P commands unidirectional converter-inverter model response

5.2.2 Test 2: Inverter Q Commands

Figures below show the model response for several commands of reactive power.

Table 7: Q commands unidirectional inverter model response

Time [s]	Q command [p.u.]	Machine output [MVAr]
[1,2]	0.2	-0.66
[2, 3]	0.4	-1.32
[3, 4]	0.6	-1.98
[4, 5]	0.8	-2.64
[5, 6]	1.0	-2.77
[6, 7]	0.8	-2.64
[7, 8]	0.6	-1.92

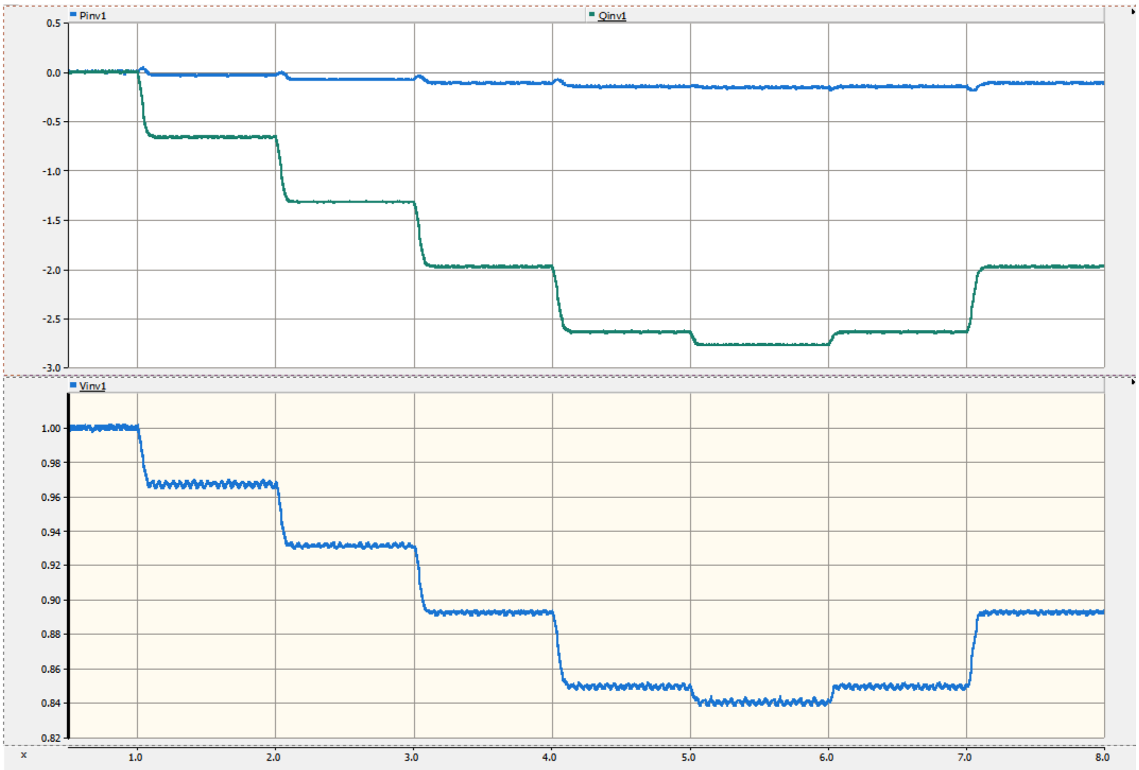


Figure 11: Q commands unidirectional inverter model response

5.3 PPC Model Results (Validation)

The PPC must be connected to the control model (EN_PPC = 1) as follows:

Figure 12: "PE_CONT" interconnection

5.3.1 Test 3: PPC POI Voltage Regulation System (VRS)

In order to enable the VRS, the user should set Qcm = 0, of the ‘PE_PPC’ model as follows:

Q Control Mode: 0 = Voltage Control	0
Tf [s]: Delay in F measurement	0.2
POI V CONTROL (Control mode = 0)	
Kp_v: Proportional gain for PPC V	0.05
Ti_v: Integral gain for PPC Voltag	0.2
Vsat: Saturation for LVRT	0.9
Vsat_hvrt: Saturation for HVRT	1.2
Tv: Delay in V measurement	0.02
Kdroop: Gain for voltage droop	0
Tdroop: Delay in the Q measurem	0.1

Figure 13: ‘PE_PPC’ configuration Enable VRS

Time [s]	V_{ref_poi} command [p.u.]
[1, 2]	1.00
[2, 10]	0.98
[10, 16]	1.02

Table 8: Voltage reference commands

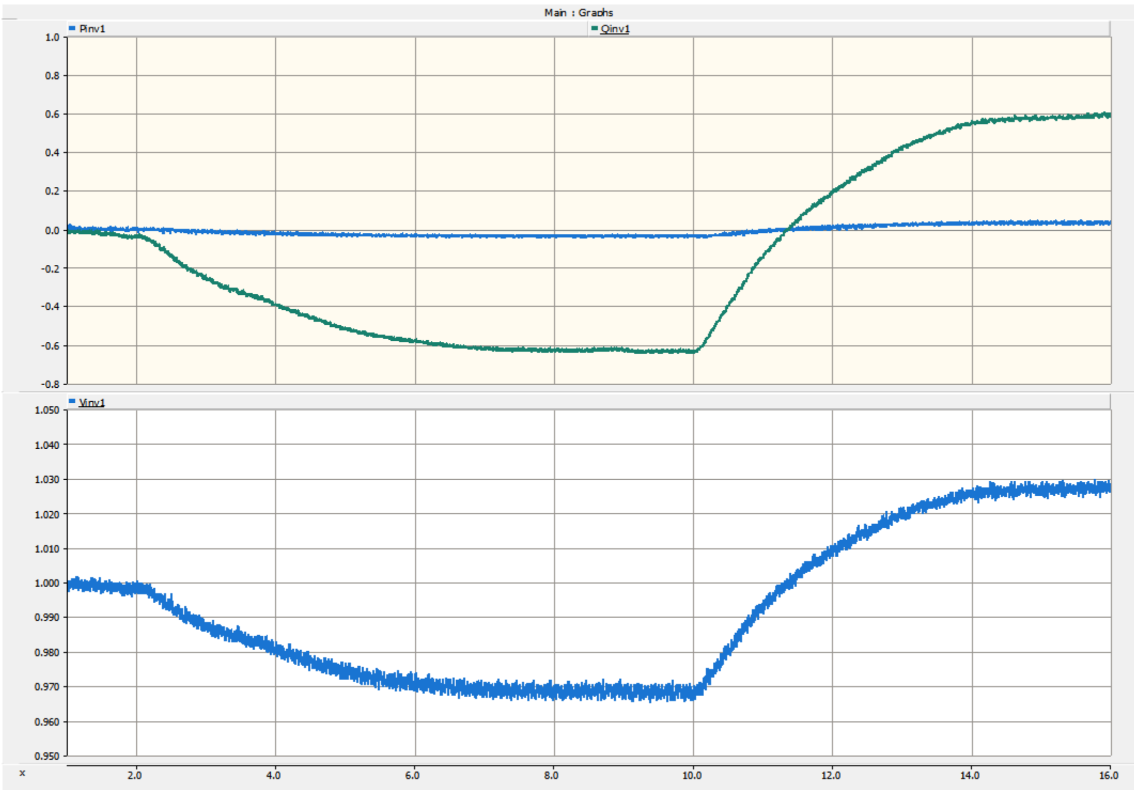


Figure 14: VRS response

5.3.2 Test 4: PPC POI Q Control

In order to enable the POI Q control, the user should set Qcm =1, of the 'PE_PPC' model as follows:

Q Control Mode: 0 = Voltage Control, 1 = Q control, 2 = PF control	1
Tf [s]: Delay in F measurement	0.2
POI V CONTROL (Control mode = 0)	
Kp_v: Proportional gain for PPC Voltage Control	0.05
Ti_v: Integral gain for PPC Voltage Control	0.2
Vsat: Saturation for LVRT	0.9
Vsat_hvrt: Saturation for HVRT	1.2
Tv: Delay in V measurement	0.02
Kdroop: Gain for voltage droop	0
Tdroop: Delay in the Q measurement	0.1
POI Q-PF CONTROL (Control mode = 1-2)	
Kp_q: Proportional gain for PPC Q Control	0.1
Ti_q: Integral gain for PPC Q Control	0.2
Qmx: Maximum Q to inverter	1
Qmn: Minimum Q to inverter	-1
Tq: Delay in Q measurement	0.02

Figure 15: "PE_PPC" configuration Enable POI Q Control

Time [s]	Q_{ref_poi} command [p.u.]
[1, 2]	0.00
[2, 4]	0.10
[4, 6]	0.20
[6, 8]	0.30

Table 9: Reactive power reference commands

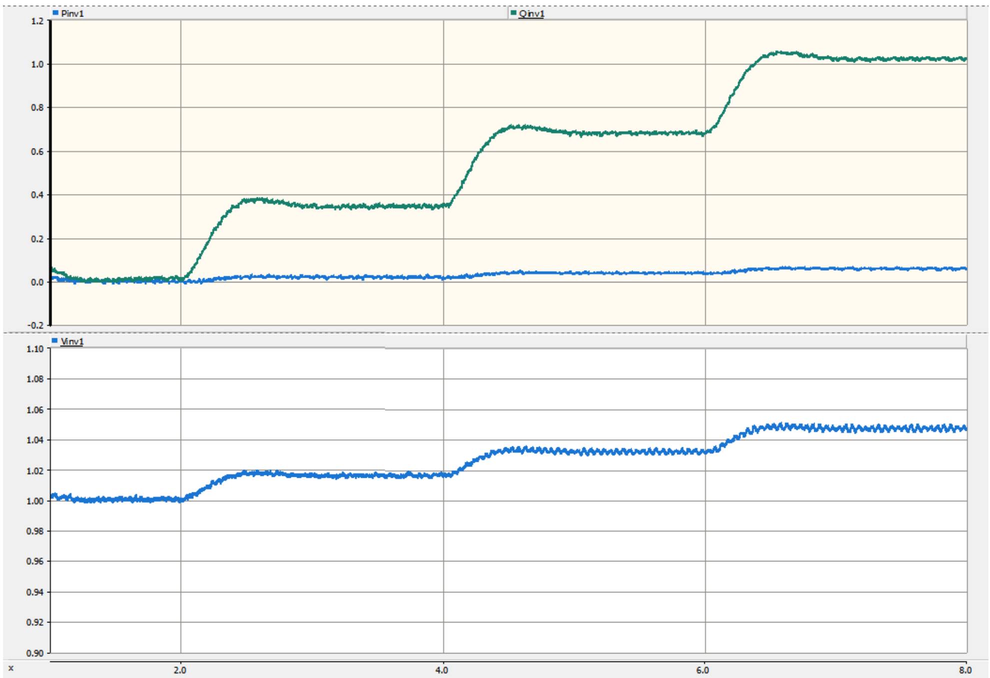


Figure 16: POI Q Control response

5.3.3 Test 5: PPC POI PF Control

In order to enable the POI Q control, the user should set Qcm =2, of the 'PE_PPC' model as follows:

Q Control Mode: 0 = Voltage Control, 1 = Q control, 2 = PF control	**2**
Tf [s]: Delay in F measurement	0.2
POI V CONTROL (Control mode = 0)	
Kp_v: Proportional gain for PPC Voltage Control	0.05
Ti_v: Integral gain for PPC Voltage Control	0.2
Vsat: Saturation for LVRT	0.9
Vsat_hvrt: Saturation for HVRT	1.2
Tv: Delay in V measurement	0.02
Kdroop: Gain for voltage droop	0
Tdroop: Delay in the Q measurement	0.1
POI Q-PF CONTROL (Control mode = 1-2)	
Kp_q: Proportional gain for PPC Q Control	0.1
Ti_q: Integral gain for PPC Q Control	0.2
Qmx: Maximum Q to inverter	1
Qmn: Minimum Q to inverter	-1
Tq: Delay in Q measurement	0.02

Figure 17: "PE_PPC" configuration Enable POI PF Control

Time [s]	PF_{poi} command [p.u.]
[1, 2]	1.00
[2, 4]	0.90
[4, 6]	1.00
[6, 8]	-0.95
[8, 10]	1.00

Table 10: Power factor reference commands

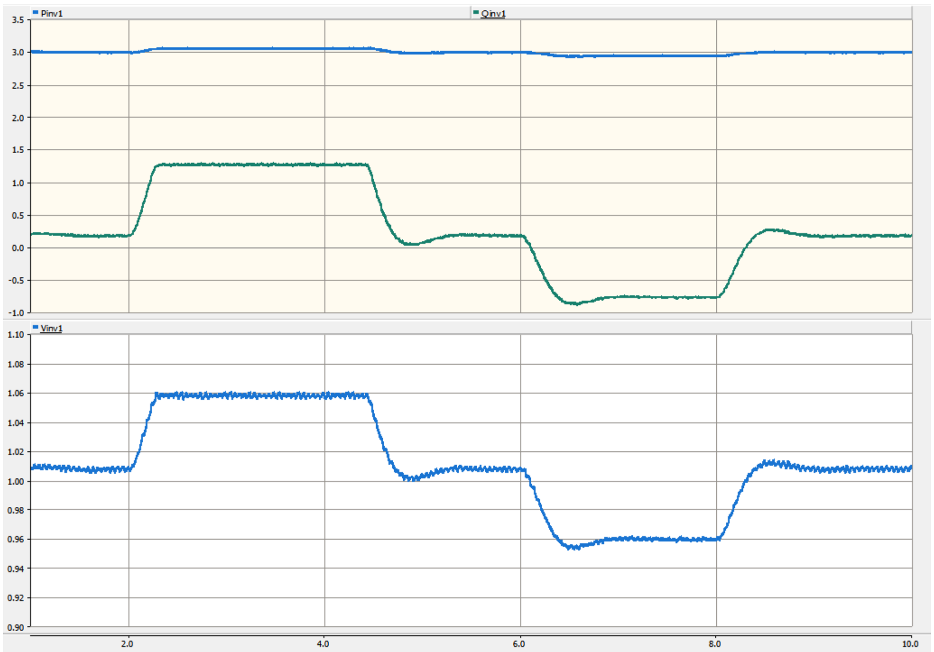


Figure 18: POI PF Control

5.3.4 Test 6: PPC Frequency Control

Figure below shows the *Frequency Regulation* algorithm (FR). The frequency deviations have been performed by changing grid frequency (Fpu).

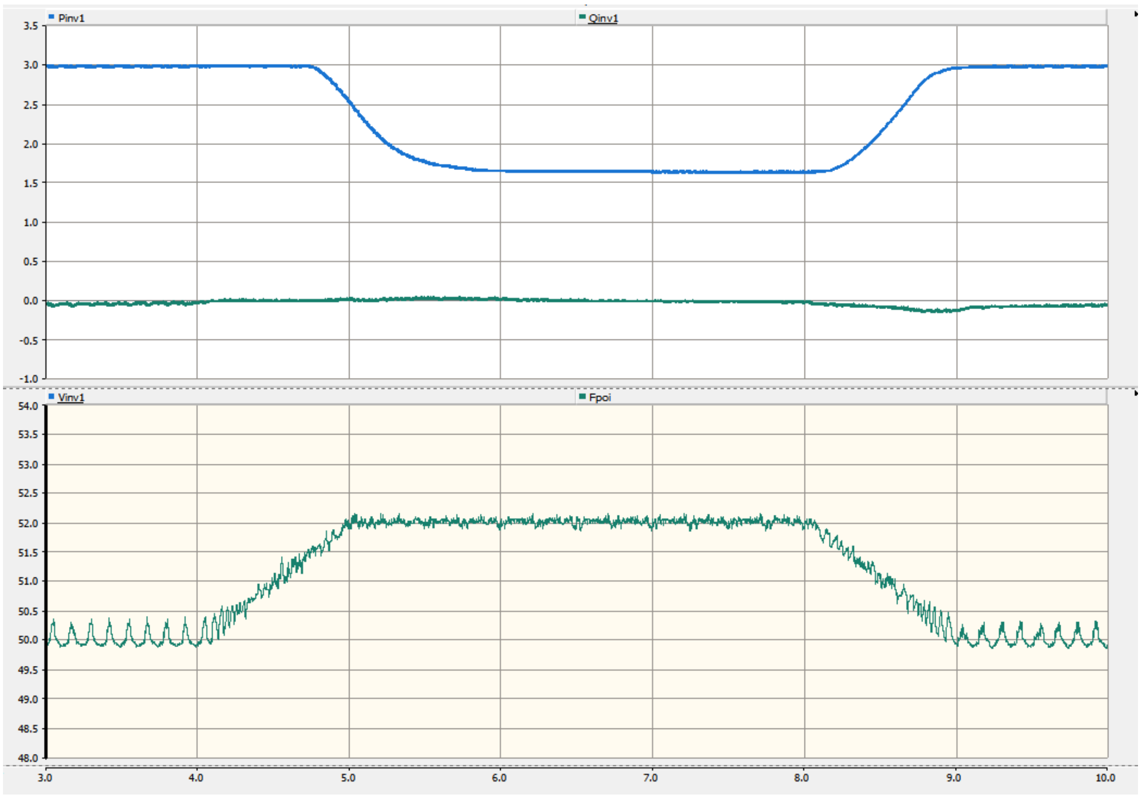


Figure 19: PPC frequency response

5.4 Low Voltage Ride Through (Validation)

5.4.1 Test 7: LVRT mode = 0 (Iq = K_{LVRT}*(Vset_lvrt-Vret); Id = 0) (Validation)

Figure below shows the model response against LVRT events. The PPC is enabled and the results correspond with Klvrt = 2.0 and Vset_lvrt = 0.85 (‘PE_CONT’), a threshold voltage of 0.85 and the following faults:

T = [4, 5] s → R = 10Ω

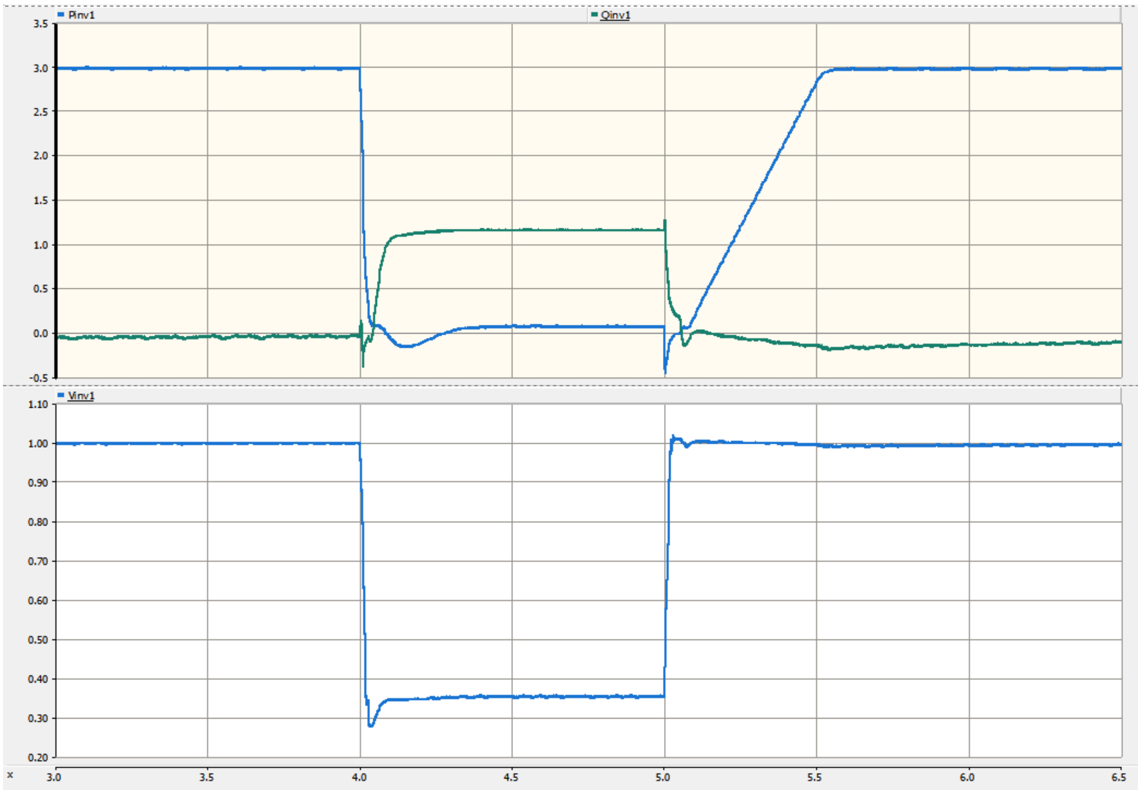


Figure 20: LVRT mode 0 inverter response

$$Q_{LVRT0} = V_{INV}*\min(K*\Delta U, 1)*Splant = 0.352*(2.0*(0.85-0.352))*3.3 = \mathbf{1.157\ MVAr}$$

$$P_{LVRT0} = 0.0\ \mathbf{MW}$$

5.4.2 Test 8: LVRT mode = 1 ($Iq = Iq_{prev} + K_{LVRT}*$ (Vset_lvrt-Vret); $Id = Id_{prev}$; $P_{priority}$) (Validation)

Figure below shows the model response against LVRT events. The PPC is enabled and the results correspond with Klvrt = 2.0 and Vset_lvrt = 0.85 (‘PE_CONT’), a threshold voltage of 0.85 and the following faults:

T = [4, 5] s → R = 10Ω

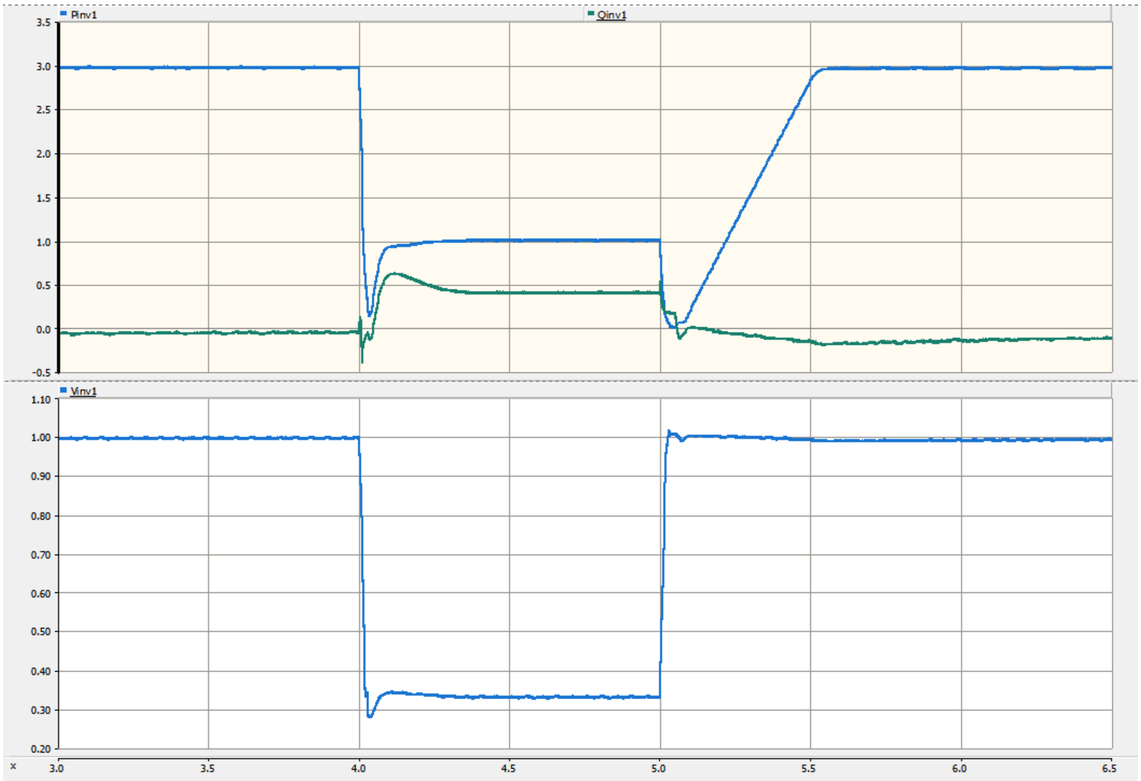


Figure 21: LVRT mode 1 inverter response

$$Q_{LVRT1} = V_{INV}*\min(Iq_{prev} + K*\Delta U, 1)*Splant = 0.328*(-0.014+(2.0*(0.85-0.328)))*3.3 = 1.0824\ MVAr$$

$$P_{LVRT1} = V_{INV}*Id_{prev}*Splant = 0.328\cdot * 0.91\cdot * 3.3 = \mathbf{0.985\ MW}$$

Priority -- $Q_{LVRT1} = V_{INV} * Sqrt(1-(Id_{prev})^2) *Splant = 0.328 * sqrt(1-0.91^2)*3.3 = \mathbf{0.448\ MVAr}$

5.4.3 Test 9: LVRT mode = 2 ($Iq = Iq_{prev} + K_{LVRT}*(Vset\_lvrt-Vret)$; $Id = Id_{prev}$; $Q_{priority}$) (Validation)

Figure below shows the model response against LVRT events. The PPC is enabled and the results correspond with Klvrt = 2.0 and Vset_lvrt = 0.85 (‘PE_CONT’), a threshold voltage of 0.85 and the following faults:

T = [4,5] s → R = 10Ω

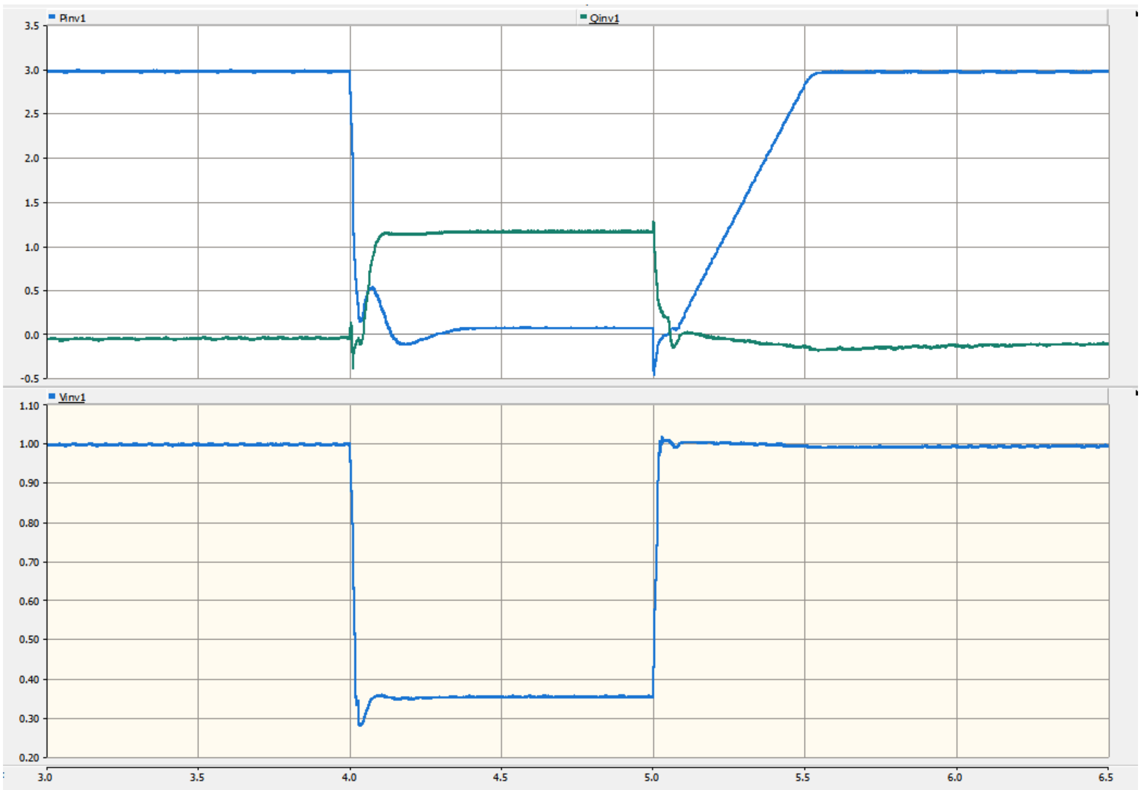


Figure 22: LVRT mode 2 inverter response

$\mathbf{Q_{LVRT2}} = V_{INV}*\min(Iq_{prev} + K*\Delta U, 1)*Splant = 0.353*(-0.014+(2.0*(0.85-0.353)))*3.3 = \mathbf{1.14\ MVAr}$

$\mathbf{P_{LVRT2}} = V_{INV}*Id_{prev}*Splant = = 0.353\cdot*0.91*3.3 = 1.06\ MW$

Qpriority -- $\mathbf{P_{LVRT2}}$ = V_{INV} * Sqrt (1- (Iq)^2) *Splant = 0.353 * sqrt (1-0.997^2)*3.3 =**0.09 MW**

5.5 Protections (Validation)

In order to enable the protections, the 'PE_CONT' En_protec should be set to 1 as follows:
All the protections values (and trip times) can be adjusted in the following parameters of the 'PE_CONT' model:

PROTECTIONS	
en_protec: =1 (enable protections) = 0 (disable protections)	1
vh1 [p.u.]: vh1 Threshold	1.3
vh2 [p.u.]: vh2 Threshold	1.28
vh3 [p.u.]: vh3 Threshold	1.2
vh4 [p.u.]: vh4 Threshold	1.1
vh5 [p.u.]: vh5 Threshold	1.1
vl1 [p.u.]: vl1 Threshold	0
vl2 [p.u.]: vl2 Threshold	0.3
vl3 [p.u.]: vl3 Threshold	0.5
vl4 [p.u.]: vl4 Threshold	0.8
vl5 [p.u.]: vl5 Threshold	0.8
t_vh1 [s]: trip time vh1	0.06
t_vh2 [s]: trip time vh2	0.2
t_vh3 [s]: trip time vh3	1
t_vh4 [s]: trip time vh4	9999
t_vh5 [s]: trip time vh5	9999
t_vl1 [s]: trip time vl1	1
t_vl2 [s]: trip time vl2	10
t_vl3 [s]: trip time vl3	21
t_vl4 [s]: trip time vl4	9999
t_vl5 [s]: trip time vl5	9999
fh1 [Hz]: Threshold fh1	54
fh2 [Hz]: Threshold fh2	53
fh3 [Hz]: Threshold fh3	52.5
fh4 [Hz]: Threshold fh4	52
fh5 [Hz]: Threshold fh5	51.5
fl1 [Hz]: Threshold fl1	45
fl2 [Hz]: Threshold fl2	45.8
fl3 [Hz]: Threshold fl3	46.8
fl4 [Hz]: Threshold fl4	48
fl5 [Hz]: Threshold fl5	48.6
t_fh1 [s]: Trip time fh1	0.01
t_fh2 [s]: Trip time t_fh2	160
t_fh3 [s]: Trip time t_fh3	1000
t_fh4 [s]: Trip time t_fh4	1800
t_fh5 [s]: Trip time t_fh5	9999
t_fl1 [s]: Trip time t_fl1	0.01
t_fl2 [s]: Trip time t_fl2	160
t_fl3 [s]: Trip time t_fl3	1000
t_fl4 [s]: Trip time t_fl4	1800
t_fl5 [s]: Trip time t_fl5	9999

5.5.1 Test 10: High Voltage Protection

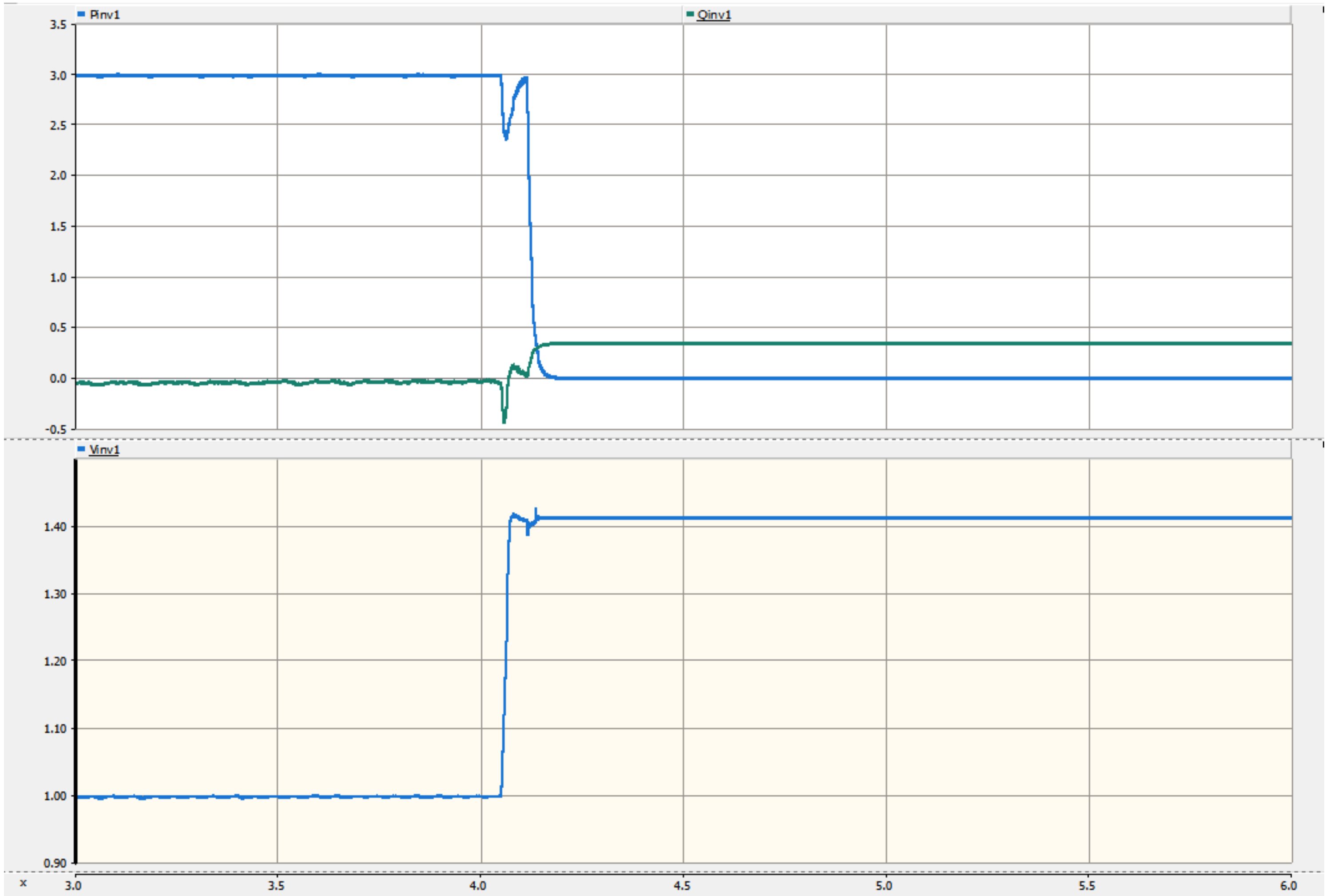


Figure 23: High voltage protection

5.5.2 Test 11: Low Voltage Protection

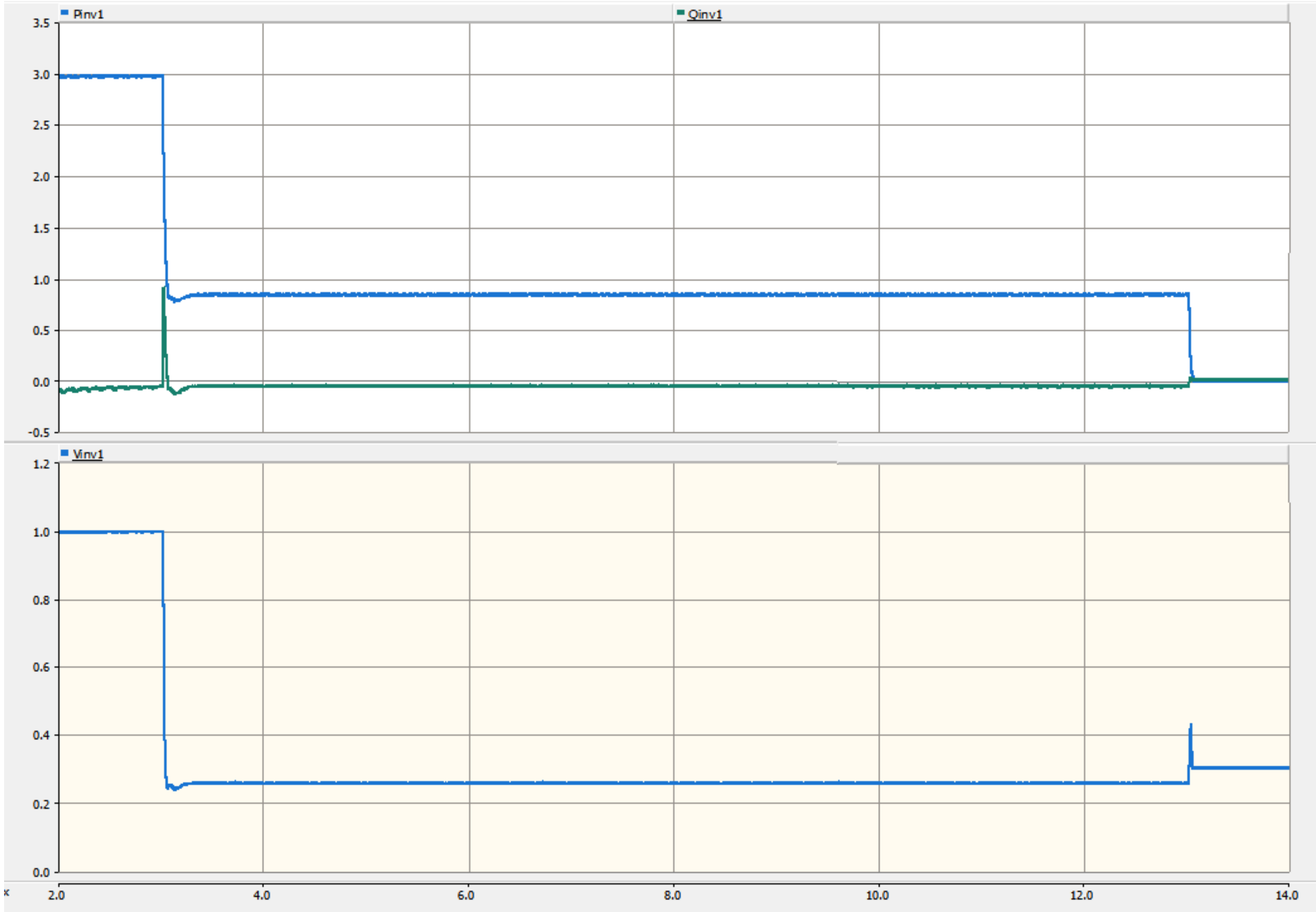


Figure 24: Low voltage protection

5.5.3 Test 12: High Frequency Protection

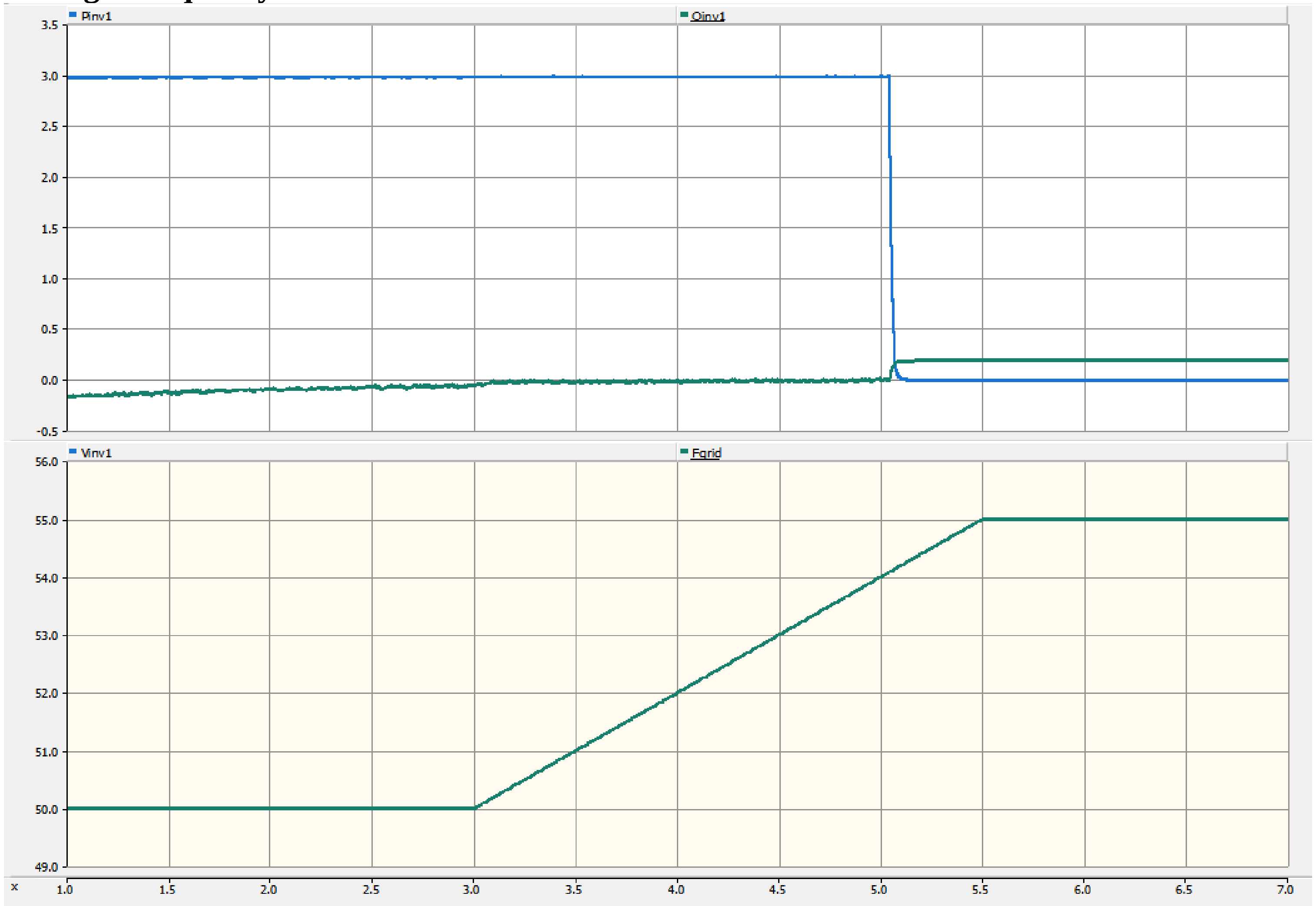


Figure 25: High frequency protection

5.5.4 Test 13: Low Frequency Protection

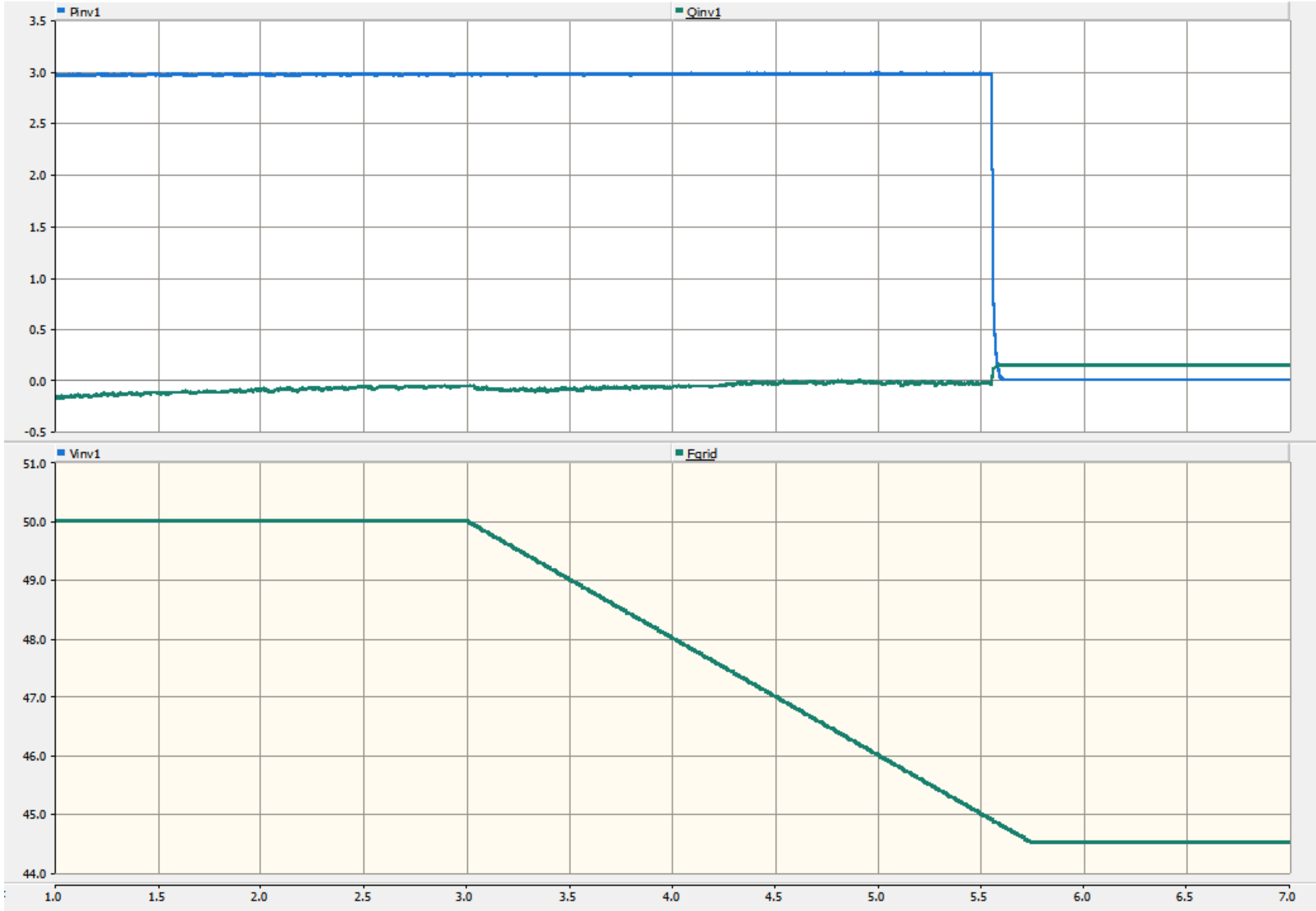


Figure 26: Low frequency protection