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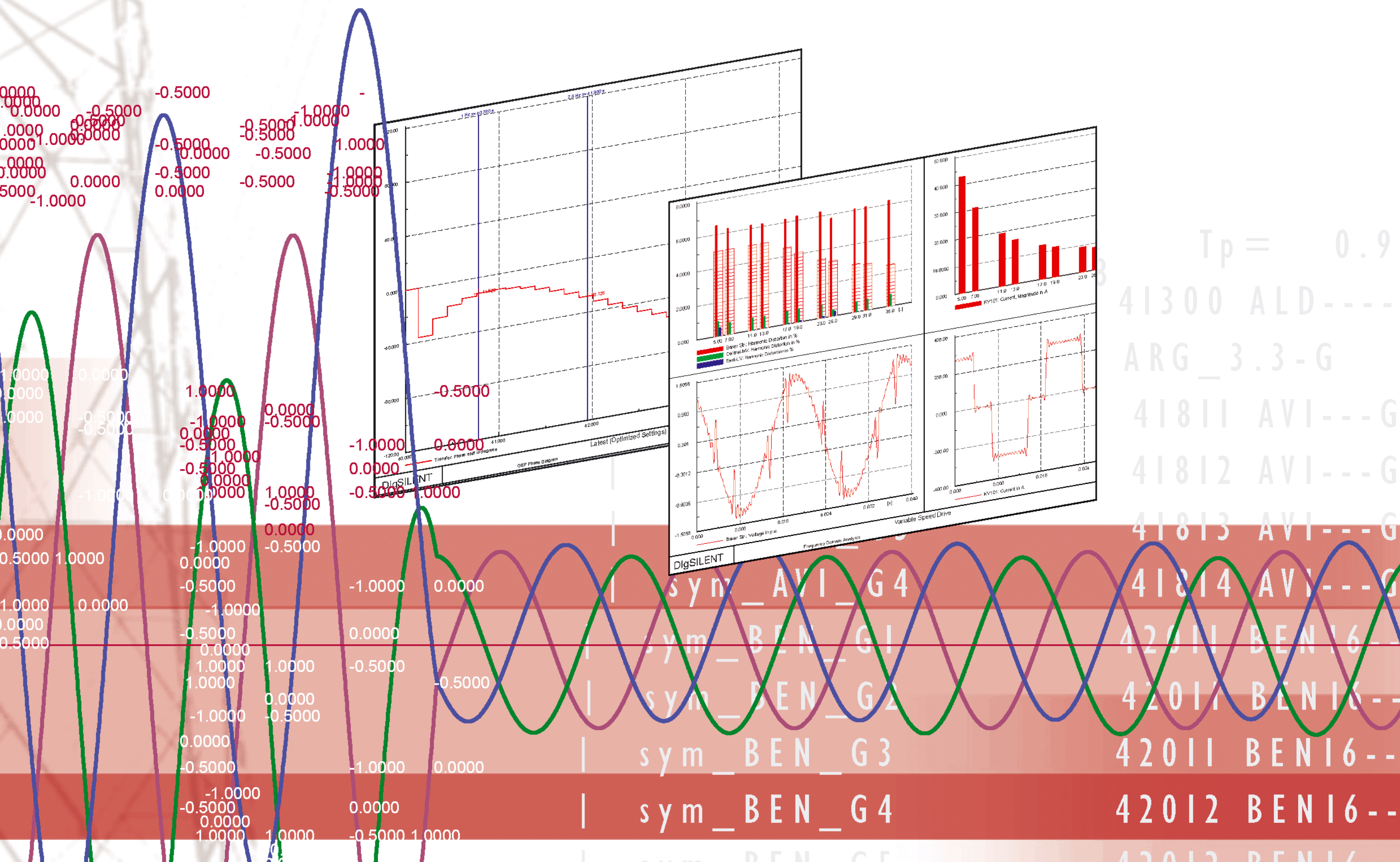
Delta Electronics PV Converter M50A – 400V PowerFactory Model Version 2.0 Model Description

Prepared for

Primara Test und Zertifizierer GmbH

Revision B



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Rev.	Prepared by	Date	Reviewed by	Date	Comments
A	S. Weigel	02.08.2019	M. Martinez	07.08.2019	Model description
B	S. Weigel	16.09.2019	M. Martinez	16.09.2019	Corrections

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1 Introduction

This document describes the model of the 55kW PV converter M50A of DELTA Electronics for 400V, as implemented in DIgSILENT *PowerFactory Version 2019*. The model can be used in this and later versions.

The model is provided in the *PowerFactory* file *"P1940-Delta-M50A-PFD01-R01-V01-ModelOpen.pfd"*. An encrypted version of the model is provided in the *PowerFactory* file *"P1940-Delta-M50A-PFD02-R01-V01-ModelEnc.pfd".* The converter controls respond to both balanced and unbalanced faults.

The MD5 check sum:

`P1940-Delta-M50A-PFD01-R01-V01-ModelOpen.pfd` `8e86b17b9cc4cc1679f125c3eafda437`

`P1940-Delta-M50A-PFD02-R01-V01-ModelEnc.pfd` `cdfea0476cb365bf69ebd0ebcd70401f`

The model includes the following functions:

1. Reactive power control
2. Power factor control
3. Converter current control and current limiting
4. Reactive current injection during grid faults (voltage support)
5. Over frequency power reduction
6. Under frequency power ramp up
7. Protection (with disconnection from the grid)

The model was prepared on the basis of the 88 kW model developed in earlier projects (see also documentation provided by DELTA Electronics [4]), as well as subsequent clarifications. Some parts of the model utilise *PowerFactory*'s "built-in" code. This applies, for example, to the converter (which is modelled as a current source). Other parts of the models, such as the converter controls, were prepared in DSL (DIgSILENT Simulation Language). The DC side was not considered since the grid side control represents the behaviour of the converter already very well. The DC voltage control was simplified by a constant active power output control (in case of undisturbed operation).

The submodels are described in Section 2. Section 3 provides guidance on the use of the models, and section 4 contains the conclusions.

The model has been validated by comparing test measurements with simulated results. Balanced and unbalanced voltage dips were considered in the validation. In the case of unbalanced faults, the phase voltages at the converter terminals were arranged as they are expected to appear in the case of a phase-to-phase fault in a compensated medium-voltage network, assuming that the converter is connected to the medium-voltage network via a transformer having the vector group Dy1.

The model was also successfully tested for plausible behaviour within the quasi-stationary operation according to VDE-AR-N 4110 chapter 10.2.1.2.

2 Model Description

The single-line diagram of the PV converter model, as well as a simplified power system model, is shown in Figure 1. The converter is represented by the *PowerFactory* element Static Generator (Figure 2) which is set up to act as a current source. The initial operating point is set within this element (Figure 3). In load-flow calculations the operating point of the converter is limited to be within the capability diagram shown in Figure 4.

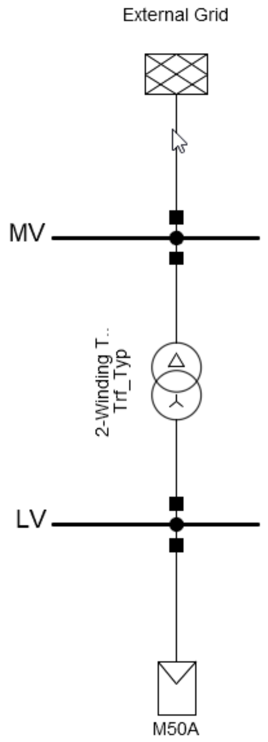

Figure 1: Single line diagram

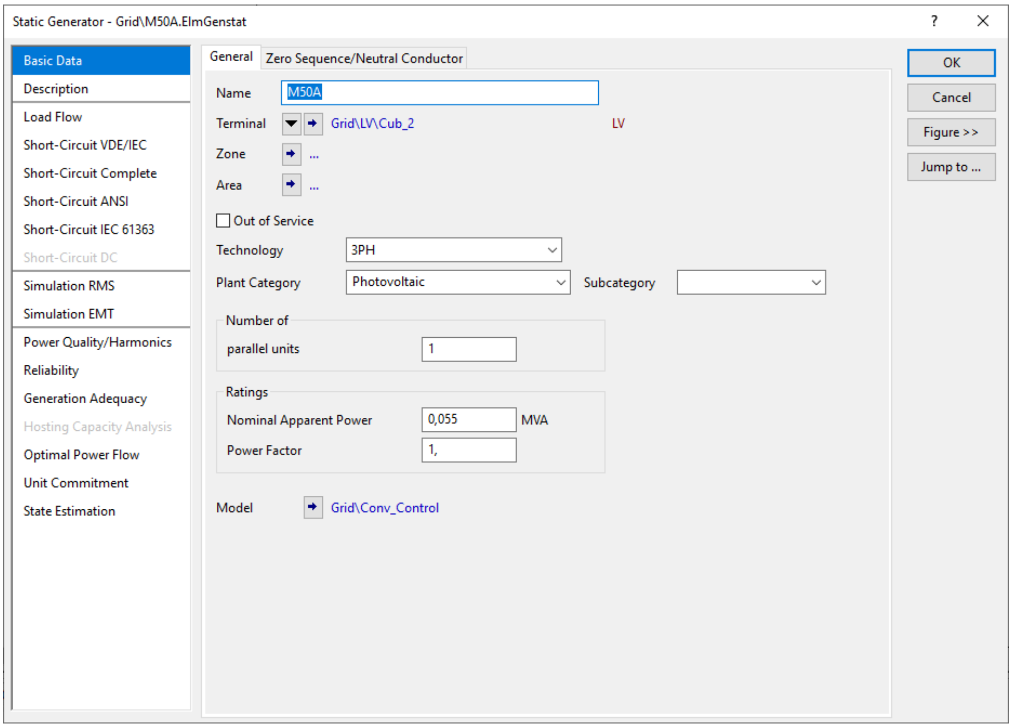

Figure 2: Static generator model settings

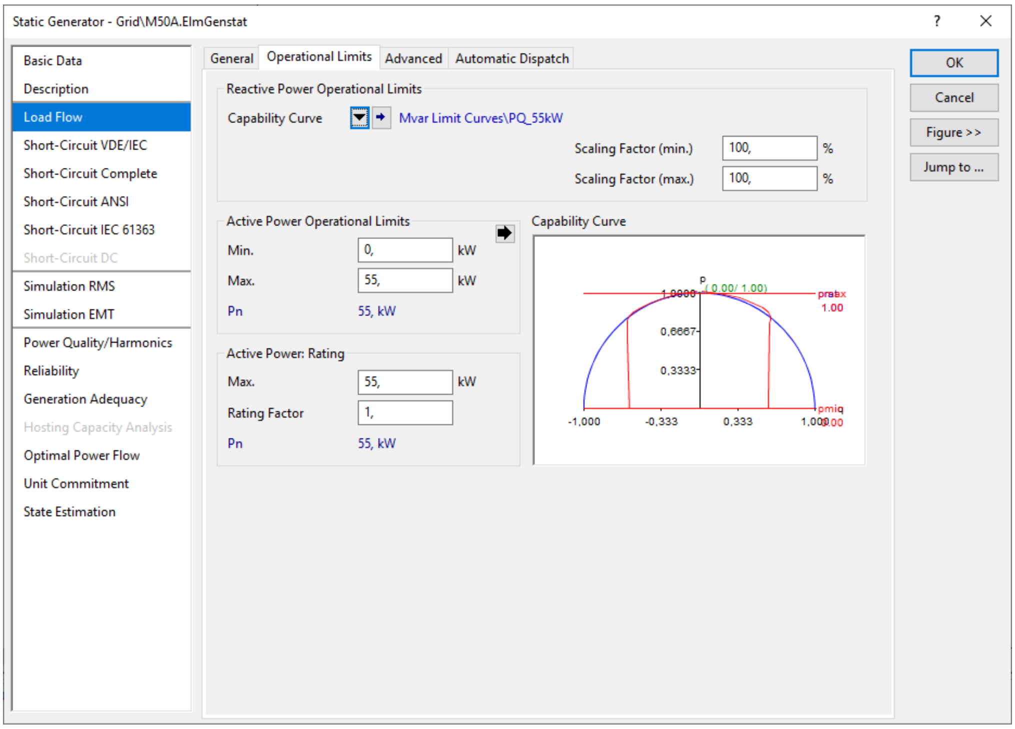

Figure 3: Static generator model settings (second part)

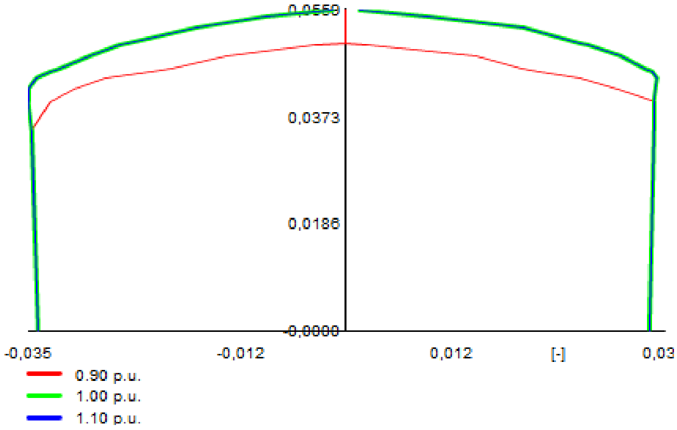

Figure 4: Capability diagram of M50A converter –in per unit

In time-domain simulations the static generator model acts as a current source. Its current references are calculated in the separate DSL model "Current_Control". The current references are calculated in a dq-axis reference frame, which is defined by the angle of the converter AC voltage. The angle is measured using a PLL (phase-locked loop). The connections between the static generator model, the Current_Control model and the phase measuring device are shown in Figure 5. That figure also shows the interconnections between the mentioned models and other sub-models, whose functions are summarised below. More detailed descriptions are given in subsequent sections of this report.

The model "Current_Control" receives an active current reference and a reactive current reference from a DC voltage controller model and a reactive power controller model. The model "Current_Control" also receives the voltages at the terminals of the converter. It uses these to detect a fault in the power system and to distinguish between a balanced and unbalanced fault. In the event of a fault, the model calculates special current references to support the network voltage whilst also respecting the current limits of the converter. The active current is kept at a value to ensure constant active power output during undisturbed operation.

The model "Q_control" calculates the reactive current reference during normal operation (i.e. no fault in the power system) according to an integral control. It regulates either reactive power or power factor, depending on its settings.

The model "Protection" disconnects the static generator model from the power system model in the event of prolonged and excessive voltage excursions.

There are five measuring elements, one for the measurement of active and reactive power, two for the measurement of converter terminal voltage, one for measuring the grid frequency and one for the measurement the voltage angle.

Control_Frame:

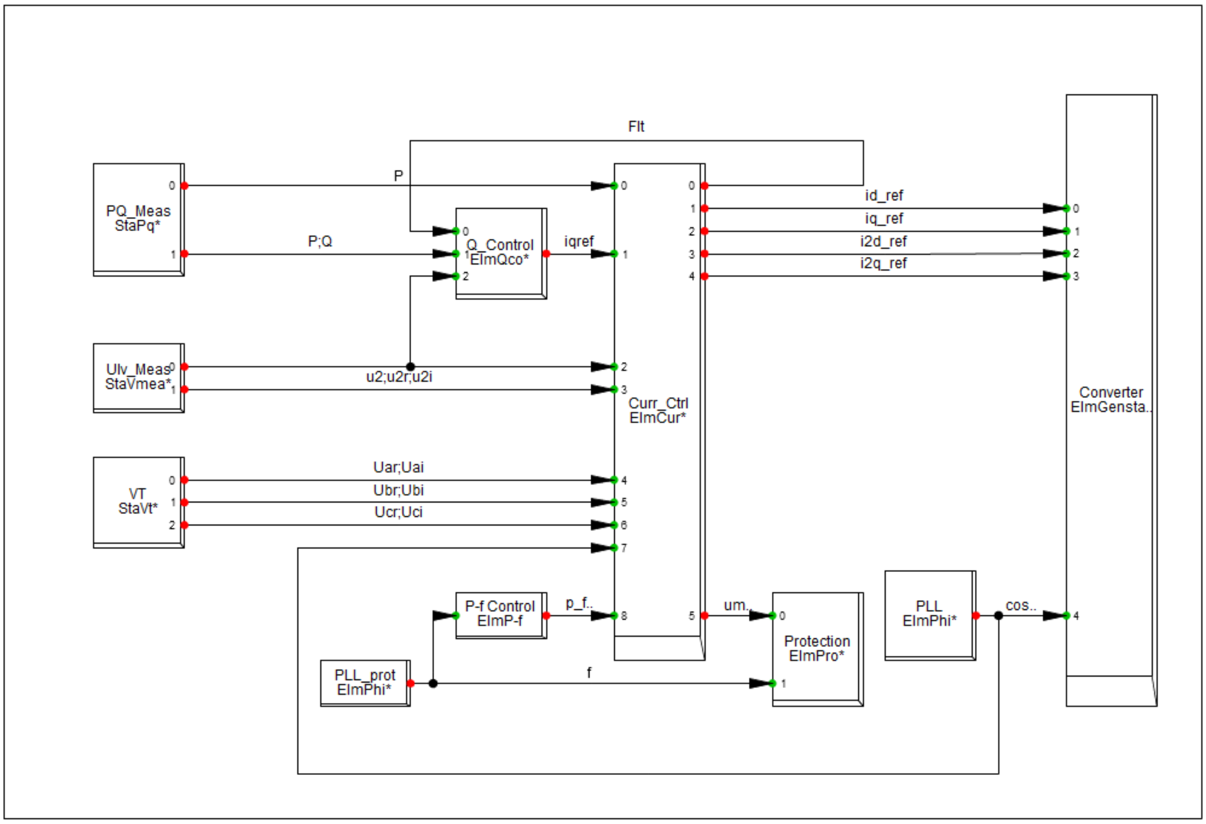

Figure 5: Frame

2.1 Current control

A block diagram of the model is shown in Figure 6. The model has the inputs "p_ref_high_prio", "p_ref_low_prio" and "iqref", which are the active power (with high and low priority) and reactive current references. The signal "iqref" is calculated in "Qcontrol". The two input signals "p_ref_high_prio" and "p_ref_low_prio" can be used to simulate curtailment. The signal with the high priority will be considered for power reduction even if there is a frequency event ongoing.

The current is limited to the minimum of imax and Smax/u, where imax is a parameter, Smax is the maximum apparent power and u is the voltage. In normal operation the reactive current is limited to the lower of imax and Smax/u, and the active current is limited to $\pm\sqrt{\min(i\max, S\max/u)^2 - iqref^2}$.

The model also has the inputs "u", "Uar", "Uai" etc., which represent the positive- and negative-sequence voltage in per unit and the phase-to-ground voltages in V, both at the AC terminals of the converter. A time constant Tmu is included to represent the voltage measurement lag. The input "u" is used to calculate the pre-fault voltage. The other inputs are used to detect a fault in the power system, and to calculate an additional reactive current. The additional reactive current is calculated according to the characteristic in Figure 7, where Uo is the pre-fault voltage. The pre-fault voltage follows the actual voltage "u" with a time constant of "Tu", but if "Uo_pre" is set to 0 then a pre-fault voltage of 1.0 p.u. is assumed. A fault is detected if the voltage is outside the band Uo-Ut or Uo+Ut for a time period of "Tpick". During a fault, the reactive current reference is either the additional reactive current (from Figure 7), or the sum of this current and the pre-fault reactive current, depending on the setting "Iq_pre". The pre-fault reactive current follows the actual reactive current with a time constant "Tq". In the event of a fault, the active current reference is limited to "id_flt", and the reactive current is limited to either "imax_3ph" or "imax_2ph", depending whether the fault is balanced or unbalanced. A fault is regarded as unbalanced if the difference between the maximum and minimum phase voltage exceeds 10%.

In reality the converter controls set the active current reference to id_flt during a fault instead of limiting it to that value, but the actual active current may differ from id_flt due to additional control actions within the current control loops. These additional control actions are not included in the model, and instead the active current is limited to id_flt. This difference between the model and the actual controller has been discussed with DELTA Electronics in detail.

During unbalanced faults the reactive current is limited to "imax_2ph". At the same time a negative sequence current is injected which is proportional to the negative sequence voltage.

The outputs "idr" and "iqr" follow the limited current references with a time constant of "Tcc", which represents (in a simplified way) the response time of the converter. These outputs set the currents of the static generator model, which acts as a current source. The output "Flt" is used to hold the integrator in the reactive power controller during power system faults.

The parameters are summarised in Table 1.

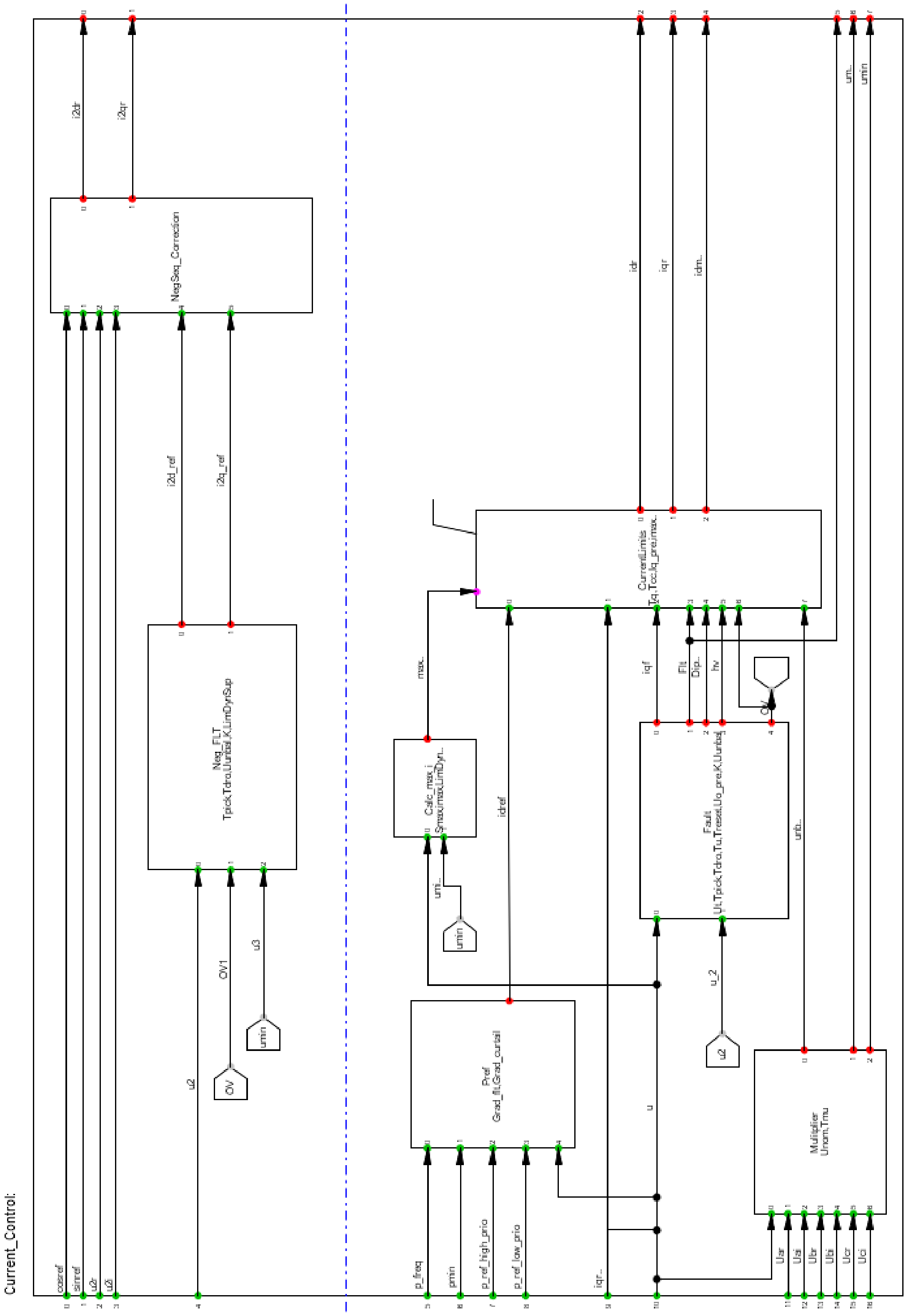

Figure 6: Model Current_Control

Table 1: Parameter Current Control

Name	Value	Unit	Description
Smax	1,05	p.u.	Apparent power limit
imax	1,1	p.u.	Current limit
LimDynSup	0	0/1	Limited dynamic LVRT support
Tq	0,04	s	Pre-fault reactive current delay time
Tcc	0,005	s	Equiv. converter reaction time
Iq_pre	1	1/0	Consider pre-fault reactive current
imax_3ph	1,1	p.u.	Reactive current limit, balanced fault
imax_2ph[1]	1,1	p.u.	Reactive current limit, unbalanced fault
id_flt	0,34	p.u.	Active current during fault
Ramp_Id	30	p.u.	Post-fault active current ramp rate
K	2		Slope diq/du characteristic
Ut	0,1	p.u.	Reactive support, voltage dead-band
Tpick	0,02	s	Fault mode, delay on start
Tdro	0	s	Fault mode, delay on exit
Tu	0,4	s	Pre-fault voltage delay time
Treset	0,5	s	Reactive support, delay on exit
Uo_pre	1	1/0	Consider pre-fault mean voltage
Uunbal	0,07	pu	Threshold for negative sequence voltage
Unom	400	V	Rated voltage
Tmu	0,01	s	Voltage filter time constant
Grad_flt	10	%/min	Power gradient after fault
Grad_curtail	30	%/min	Power gradient curtailment

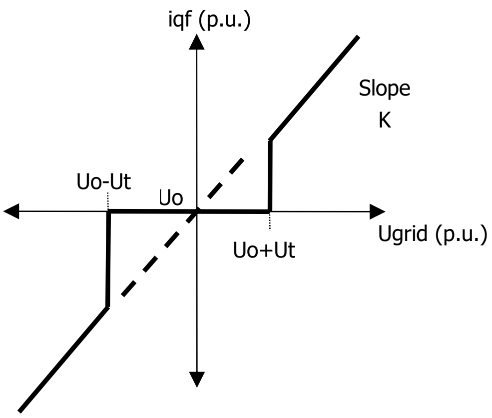

Figure 7: Additional reactive current

2.2 Reactive power control

A block diagram of the reactive power controller is shown in Figure 9. The inputs are reactive power reference "Qref", power factor reference "cos_ref", reactive power "Q", active power "P" and fault signal "Flt". The model regulates either reactive power or the power factor, depending on the setting of "Mode". The input to the integrator is either "K" or "K_band", depending if the difference between the reference and the measured quantity is within or outside "Band". The reference reactive power is limited to "Q_lim" and the reference power factor is limited to "cosphi_lim". The output reference current "iqref" is limited to Qlim/u, where u is the voltage and Qlim is obtained from a vector, which represents a part of the capability diagram. Qlim is limited to the lower of 0.63 and the active power (Figure 8).

In the event of a network fault the input to the signal "Flt" has the value 1.0 and the input to the integrator is set to 0.0. In addition, to prevent toggling, the input to the integrator is set to zero if its input is less than 0.0005.

The references "Qref" and "cos_ref" are calculated automatically when the model is initialised, i.e. these values reflect the steady-state condition given by the load-flow calculation. Positive values of reactive power reference or power factor reference refer to capacitive (over-excited) operation, and negative values refer to inductive (under-excited) operation.

Table 2: Parameter Reactive Power Control

Name	Value	Range	Unit	Description
Mode	0	0 - 1	0/1	0=Q, 1=cos(phi)
Ki	2	2	1/s	Integral Gain
Kp	0,5	0,5	-	Proportional Gain
Q_lim	0,75	0,75	p.u.	Reactive power reference limit
cosphi_lim	0,8	0,8	p.u.	Power factor reference limit

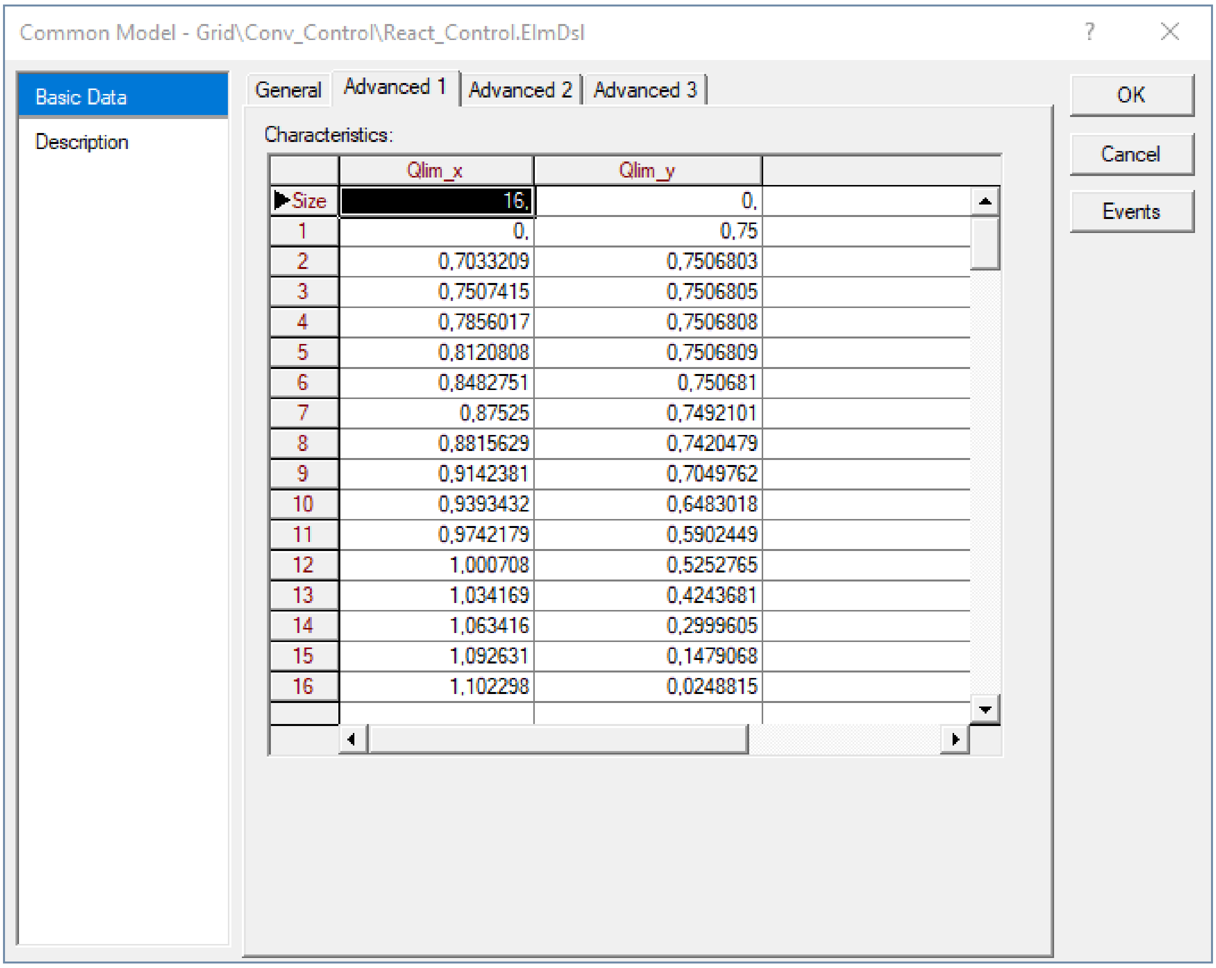

Figure 8: Settings of reactive power controller (reactive power mode, second part)

Qcontrol:

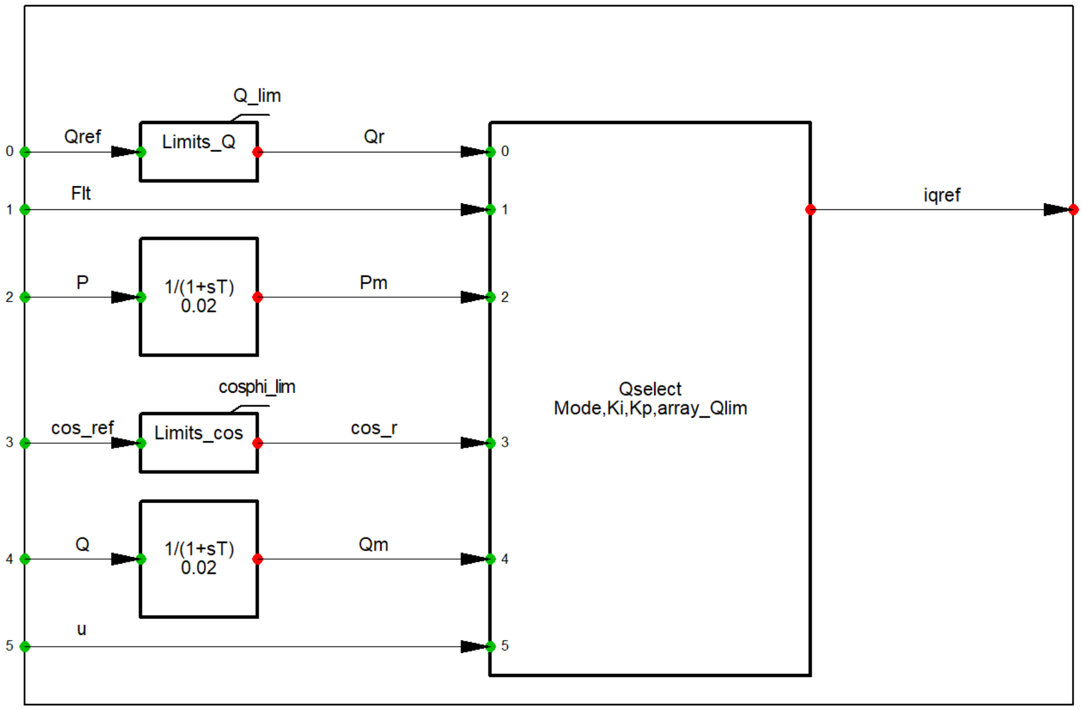

Figure 9: Model Qcontrol

2.3 Protection

The model "Protection" trips the static generator if any phase voltage is lower than "Umin1" for the time "Tmin1", lower than "Umin2" for the time "Tmin2", or higher than "Umax" for the time "Tmax". The model also trips the static generator if the frequency is lower than "fmin" for a time "T_fmin", or higher than "fmax" for a time "Tf_max".

The frequency is measured by a separate measurement device "FreqMeas". The configuration is shown in Table 3. The configuration of the frequency measurement PLL is shown in Figure 10.

Table 3: Parameter Protection

Name	Value	Range	Unit	Description
Umin1	0,2	0,2	p.u.	Pick-up voltage, under-voltage 1
Tmin1	0,2	0,2	s	Pick-up time 1, under-voltage
Umin2	0,9	0,9	p.u.	Pick-up voltage, under-voltage 3
Tmin2	3	3	s	Pick-up time 2, under-voltage
Umax	1,2	1,2	p.u.	Pick-up voltage, over-voltage
Tmax	0	0	s	Pick-up time, over-voltage
fmin	47,5	47,5	Hz	Pick-up frequency, under-frequency
fmax	51,5	51,5	Hz	Pick-up frequency, over-frequency

Name	Value	Range	Unit	Description
Tf_min	0,1	0,1	s	Pick-up time, under-frequency
Tf_max	0,1	0,1	s	Pick-up time, over-frequency

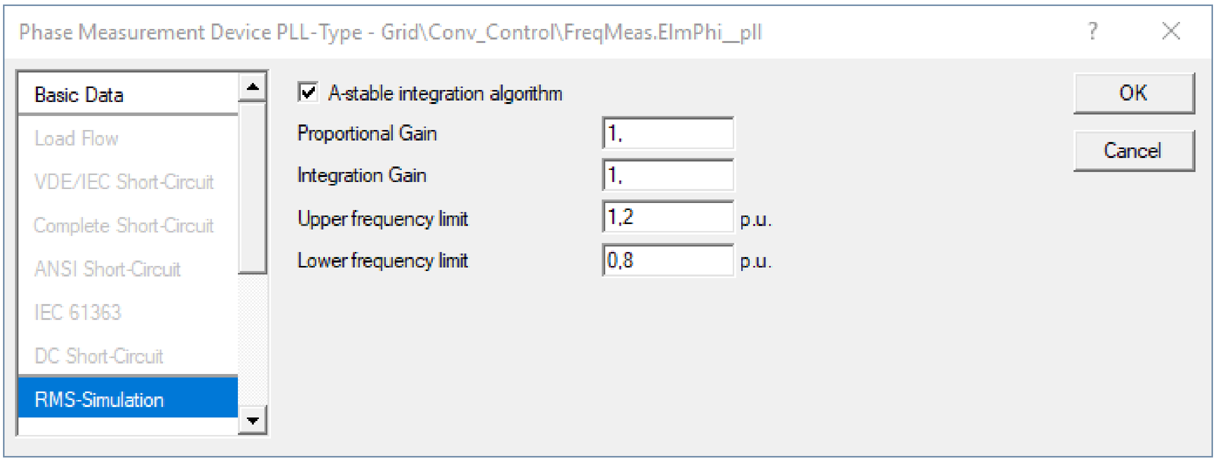

Figure 10: Settings of frequency measurement device

2.4 P-f Control

The model P-f Control contains an active power reduction function in case of over frequency as well as a power increase function in case of under frequency events. Both functions can be separately activated and configured. The under frequency function works only if the active power was curtailed during the simulation using the input signal "p_ref" of the model "Curr_Control". The signal "p_ref" can be changed via parameter events or via signal from a custom made DSL model.

The control structure of the P-f Control model is shown in Figure 11 the parameters are listed in Table 4.

P-f Control:

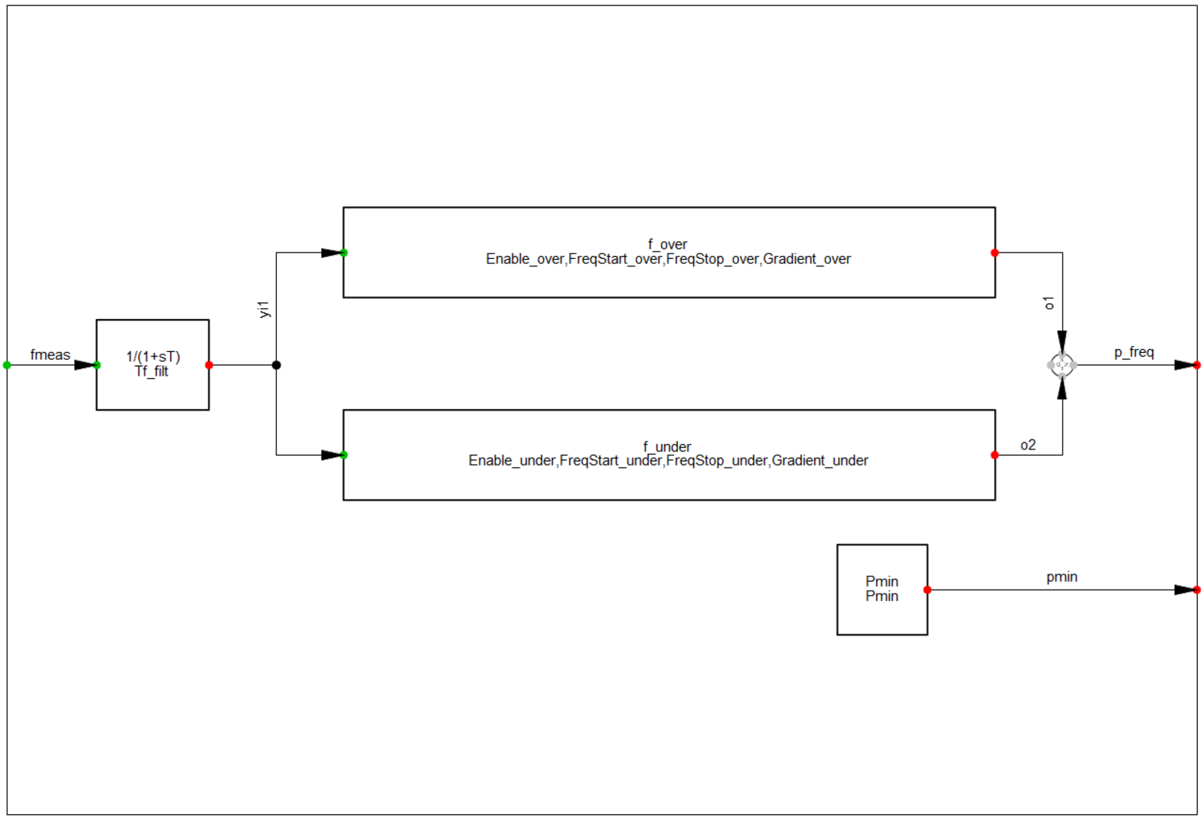

Figure 11: Block definition of the P-f Control model

Table 4: Parameter P-f Control

Name	Value	Range	Unit	Description
Tf_filt	0,01	0,01	s	Frequency filter time constant
Enable_over	1,	0 - 1	0/1	1 to enable over frequency power reduction
FreqStart_over	50,2	> 50	Hz	Start threshold for over frequency
FreqStop_over	52,7	> 50	Hz	End point for over frequency power reduction
Gradient_over	40,	> 0	%/Hz	Gradient for reducing active power
Enable_under	1,	0 - 1	0/1	1 to enable under frequency power rampup
FreqStart_under	49,8	< 50	Hz	Start threshold for under frequency
FreqStop_under	0,	< 50	Hz	End point for under frequency power increase
Gradient_under	36,	> 0	%/Hz	Gradient for increasing active power
Pmin	0,	>= 0	pu	Lower power threshold

2.5 Phase measurement

The phase measurement is done using a model built into the PowerFactory software. The model uses a PI controller to calculate the phase. The parameters of this model are shown below (Figure 12). In the event of a severe voltage reduction the phase measurement device is halted, as described in section 2.1.

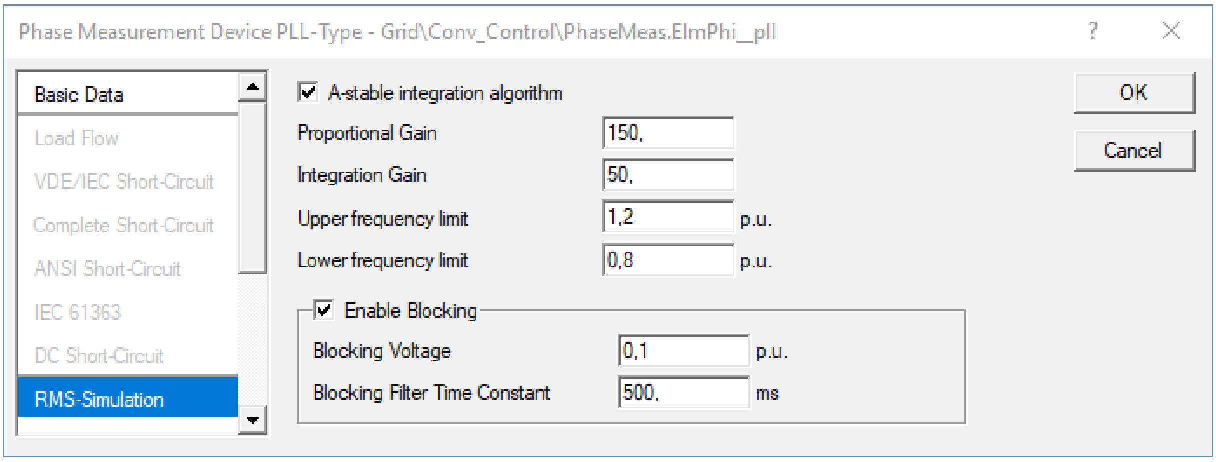

Figure 12: Settings of PLL

3 Model setup and use

1. Import the project "P1940-Delta-M50A-PFD02-Rxx-Vxx-ModelEnc.pfd" into PowerFactory 2019 (or later version), where xx represents the latest model revision and version.
2. Copy the template "Delta_M50A" into the Templates library folder of the target project.
3. Click on the toolbox icon "General Templates", select the abovementioned template and place the objects into the single-line diagram.
4. Locate the DSL model "Curr_Control" in the database. Edit it, and set the K-factor "K", as required.
5. Edit the DSL model "React_Control" to choose the mode of reactive power control in normal operation (0:constant reactive power, 1:power factor).
6. Make further changes to the parameters, if recommended by Delta Electronics.
7. Edit the static generator model and, on the load flow page, enter the active (up to 55kW) and reactive power.
8. Calculate the load flow and ensure that there are no warnings or error messages.
9. Calculate the initial conditions (RMS simulation, symmetrical or unsymmetrical network representation, recommended integration step size: 1ms constant step size).
10. Define the events and select the variables to be recorded.
11. Start the simulation.

4 Conclusions

A simulation model was developed for the M50A converter from DELTA Electronics. The model is suitable for the simulation of balanced and unbalanced faults. The logic for the response to unbalanced faults is based on an assumption that the converter will be connected to a compensated medium-voltage network via a Dy1 transformer. A phase-to-phase fault in such a network leads to a voltage depression on predominantly one phase at the converter terminals.

The model shows for very low voltage events (below 10% remaining voltage) an imprecise behaviour, regarding the reactive current infeed in proportion to the voltage dip. This behaviour is a result of the voltage angle tracking (PLL) and cannot be changed.

The M50A converter model has been validated by comparing the simulated response to measured responses to balanced and unbalanced voltage depressions. The results of the validation are contained in a separate document.

5 References

[1] Technical data provided by Delta Electronics; file name: Controller-VDE4110(M125)-2018-12-20.pdf

[2] Technical data provided by Delta Electronics; file name: FRT-VDE4110-2018-12-20.pdf

[3] Technische Richtlinien für Erzeugungseinheiten, Teil 4, Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW e.V.), Revision 8

[4] DIgSILENT GmbH; Delta Electronics RPI-M88H PV Converter, PowerFactory Model Version 2.0, Model Validation; P1870_Primara_M88H400V_REP01_R01_01.pdf