SMA GRID FORMING –
The SCS Grid Forming Manual

Applicable to
SMA SUNNY CENTRAL STORAGE UP/UP-XT
and corresponding Grid Forming Performance Packages

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1 Sunny Central Storage with Grid Forming Performance Packages

1.1 Overview on Grid Forming Applications

Grid forming with SMA Sunny Central storage can be applied for different applications:

- Microgrids / Island grids
- System Stability as Grid Service
- Enable Grid Connection in Weak Grid Areas
- Blackstart / System restoration

1.2 Grid Forming Performance for Sunny Central Storage UP (-XT)

The Sunny Central Storage UP (-XT) inverter platform can be extended with grid forming functionalities. Three different packages cover different use cases related to grid-forming:

a. GFM-SCS-00 – Grid Forming **Microgrid**– this is equivalent in functional scope to the previous "Grid Forming option"

b. GFM-SCS-01 – **Essential Synchronous** Grid Forming

c. GFM-SCS-02 – **Advanced Synchronous** Grid Forming

	Grid Forming for Microgrid	**Essential Synchronous Grid Forming**	**Advanced Synchronous Grid Forming**
	GFM-SCS-00	GFM-SCS-01	GFM-SCS-02
Droop control mode	✓	✓	✓
Blackstart capability[1]	✓	✓	✓
Inertia control mode (VSM)	-	✓	✓
Designed for grid code compliance		(✔)[3]	(✔)[3]
Current Boost for short-term performance beyond rated power[2]	Limited to rated power	Limited to rated power	✓

1. Blackstart capability requires UPS for auxiliary power, DC precharge circuit and suitable plant control (SMA Power Plant Manager with Hybrid Controller)

2. Current boost allows to exceed rated continuous power for transient events, continuous power based on specific plant design, under consideration of e.g. ambient temperature, reactive powe range, etc.

3. Grid codes are evolving towards considering grid-forming related requirements. Compliance of Synchronous GFM cannot be guaranteed due to „moving target" situation. Please refer to country/market specific recent updates.

Table 1: Scope of GFM performance packages

1.3 Disclaimer:

SCS UP(-XT) with Grid Forming Performance Packages is not compatible to existing grid codes or standards for bulk power systems. The existing inverter certification or compliance statements do not cover grid forming operation, and compliance cannot be guaranteed. Market/Country specific information on evolving standards and grid connection codes may be available, that consider grid-forming. Even if market specific compliance is aimed for, compliance cannot be guaranteed due to the rapid evolution and change of standards, market designs and certification processes.

SCS UP(-XT) with Grid Forming Performance Packages may have limitations regarding performance stated in datasheets, manuals or additional documentation. Some characteristics of grid forming control that aim at ensuring system stability and reliable operation may prevent the inverter to reach some of its specifications. This includes, but is not limited to, the inability to reach nameplate capacity (e.g. under unsymmetric load/voltage), or restrictions in accurately following external setpoints.

2 Grid Forming Control Modes

Two distinct principles are the basis for operation in grid forming mode: Droop and Inertia control. The droop control applies a proportional relation between active power and frequency, or reactive power and voltage, respectively. Inertia mode establishes, for active power path, the behavior of an emulated rotating mass which is accelerated or decelerated by the measured active power.

Figure 1 shows the high level control block diagram of the SCS Grid forming controls. From plant control the references are provided for voltage v_{ref}, frequency f_{ref}, active power P_{ref} and reactive power Q_{ref}.

The active power path (upper left) and reactive power path (lower left) define reference frequency f and voltage amplitude v of the internal voltage source of the inverter. The inverter is operated as AC voltage source based on the AC voltage controller that sends PWM reference to the semiconductor bridge. At the inverter AC output, active power P_{meas} and reactive power Q_{meas} are measured based on voltage and current sensor signals. These measurements are used in the active and reactive controls.

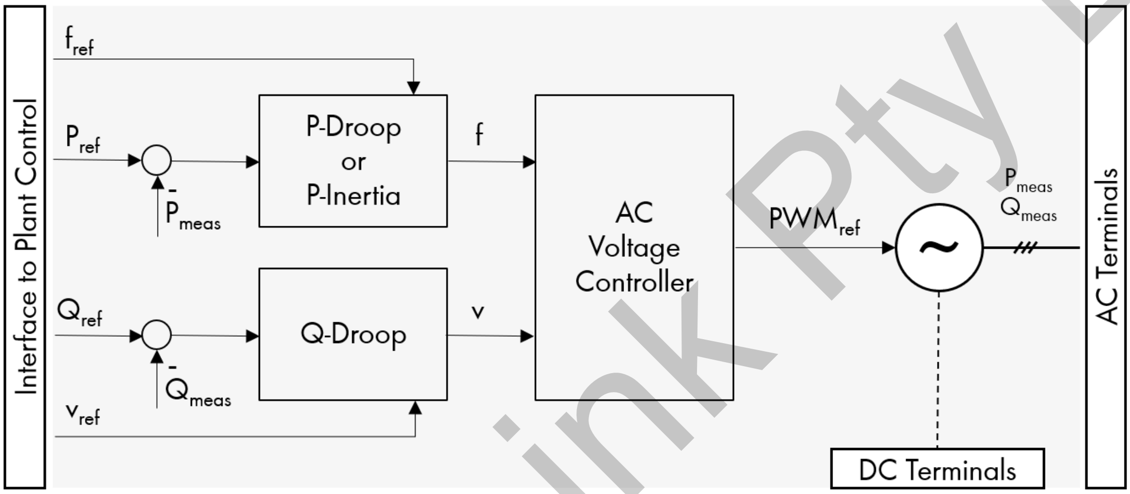


Figure 1: High level control block diagram of SCS Grid Forming Controls

2.1 Droop Control

The inverter uses droop functions to calculate references for f and V based on the active power and reactive power, respectively. The droops reduce the frequency when loaded with active power, and reduce voltage when loaded with reactive power. This allows parallel operation with generators in microgrids, without replicating the rotational machine characteristics.

The simplified equations are

$$f = f_{ref} + k_P \cdot (P_{ref} - P_{meas})$$
$$v = V_{ref} + k_Q \cdot (Q_{ref} - Q_{meas}).$$

2.1.1 P-Droop: Active power droop control

The P-Droop control scheme is shown in Figure 2.

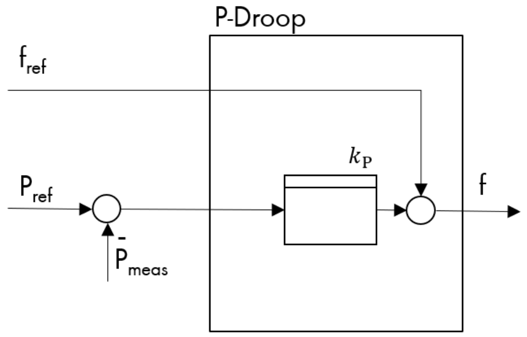


Figure 2: P-Droop control structure

The active power output and the AC frequency are coupled by the Active Power Droop. The droop slope can be adjusted by using the Parameter *GriForm.AcCtl.DrpHz* in the unit of Hz / pu. Default setting is -1 Hz/pu at Nominal active power output, so in Island operation the AC frequency will be adjusted by - 1 Hz if the device provides positive nominal active power (discharging) if there are no further adjustments of setpoints done. The slope of the droop is usually setup at commissioning and not changed during operation. Multiple inverters in parallel operation should have the same droop settings to ensure optimal operation.

During operation the operation point of an individual device can be adjusted by adjusting the reference frequency f_{ref} or by adjusting the active power setpoint P_{ref} (output at nominal frequency). Both have the same result, since both adjustments can be converted to each other by using the slope setting of the droop.

In Grid Forming Operation, the inverter control does not necessarily bring the active power output to exactly meet the active power setpoint. Power output is always dependent on other devices connected in parallel. The active power output will match the setpoint only if the inverter operates in a system that operates at a frequency equal to the setpoint frequency.

2.1.2 Q-Droop: Reactive power droop control

The Q-Droop is shown in Figure 3.

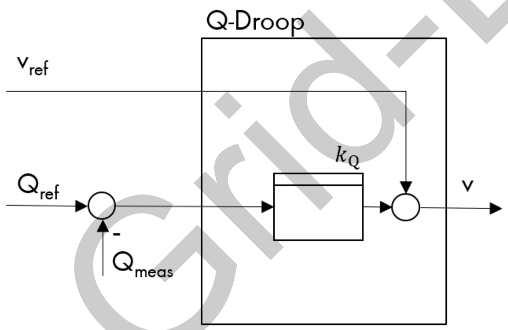


Figure 3: Q-Droop control structure

The reactive power output and the AC Voltage are coupled by the Reactive Power Droop. The Droop slope can be adjusted by using the Parameter GriForm.AcCtl.DrpVol in pu/pu. Default setting is 0.05, which reflects in a voltage adjustment of 5% of Nominal Voltage at rated reactive power output, if there are no further adjustments of Setpoints done. The slope of the Droop is usually setup at commissioning and is usually not changed during operation. Multiple SCS in parallel operation should have the same droop settings to ensure optimal operation.

During operation, the operational point of an individual device can be adjusted by changing the reference voltage v_{ref} or by adjusting the reactive power setpoint Q_{ref}. (output at nominal voltage). Both have the same result, since both adjustments can be converted to each other by using the slope setting of the droop.

In Grid Forming Operation, the inverter control does not necessarily bring the reactive power output to exactly match the reactive power setpoint. Power Output is always dependent on other devices connected in parallel. The reactive power output will match the reactive power setpoint only if the inverter terminal voltage is equal to the setpoint voltage of that inverter.

2.2 Inertia Control

Based on the swing equation

$$\frac{\Delta P}{S_N} \cong -2 \cdot H_\vartheta \cdot \frac{\partial f / \partial t}{f_N}$$

the behavior of the inertia is implemented as shown in Figure 4. The integrator replicates the rotational frequency of the emulated inertia. An additional damping control provides damping.

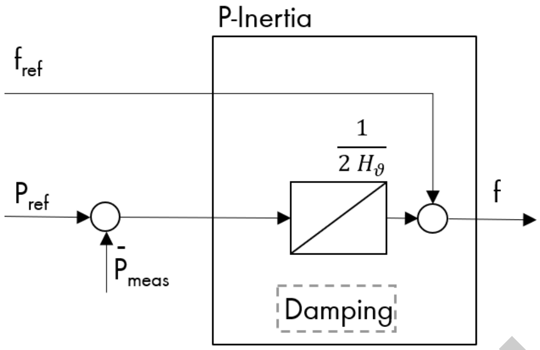


Figure 4: P-Inertia control schematic

The main parameters of P-Inertia are:

- GriForm.AcCtl.InertiaThetaH — H constant – defines the amount of emulated inertia
- GriForm.AcCtl.InertiaHzDmp — Damping parameter – defines the damping characteristic.

Inertia: The H-constant – in analogy to a rotating machine – describes the amount of emulated inertia, related to the equivalent rotational energy E_{kin}:

$$E_{\mathrm{kin}} = H \cdot P_{rated}$$

When designing the inertia reserve, the associated power reserve ΔP needs to be considered. It depends on the design $\mathrm{ROCOF}_{\max}$ criterion:

$$\Delta P = \frac{\mathrm{ROCOF}_{\max}}{f_0} 2\, E_{\mathrm{kin}}.$$

The H constant applies a scaling of the power response to a certain design $\mathrm{ROCOF}_{\max}$:

$$\frac{\Delta P}{P_{rated}} = \frac{\mathrm{ROCOF}_{\max}}{f_0} 2\, H\,.$$

The choice of H constant is limited by power limits of the inverter but also the connected battery. To achieve a guaranteed response of inertia, the power reserve needs to be available from inverter and battery.

In addition, excessively high H constants will introduce cyclic loads that will accelerate equipment ageing. This depends on the expected transients in a specific grid connection point. As guidance, values greater than H=6s, or grid connections with high number of significant ROCOF events need special consideration regarding load cycles.

Damping: The achievable damping is much higher than with a damper winding in a synchronous machine. The damping does not introduce steady-state active power reactions to frequency deviations (unlike in droop mode).

The settings affect not only the transient inertial response, but also speed of reaction to setpoints. And the behavior depends on the grid impedance (SCR, X/R).

SCR [POI] / HV transformer uk	GriForm.AcCtl.InertiaThetaH [s]	GriForm.AcCtl.InertiaHzDmp [Hz/pu]
10 (strong grid) / 0.12	1	-1.8
	2	-1.2
	3	-1
	4	-0.9
	5	-0.8
	6	-0.7
	7	-0.64

Table 2: Inertia and Damping typical configurations

Table 2 provides typical parameters that give reasonable damping and settling time. To achieve a well-tuned behavior of the grid-forming inverter, the damping parameter GriForm.AcCtl.InertiaHzDmp should be tuned in an EMT grid study, to reflect the specific project conditions.

Parameters must not be defined or changed without prior grid study. The study shall include all relevant operation conditions. In a grid study, the parameter configuration needs to be validated. If different settings of inertia constant and damping factor shall be used during operation, the grid study needs to consider each desired parameter configuration separately. SMA does not take any responsibility for undesired behavior, equipment damage or other adverse effects due to setting of invalid parameters.

For the UK stability pathfinder tests at SMA, a range of H=1.4s up to H=6s was considered. Values outside of that range are not officially supported.

2.3 Operating Modes (SCSOpCmd) for Inertia and Droop and related Parameters

Inertia and Droop can be enabled separately for voltage and frequency channels now:

SCSOpCmd	Name	Details	Comment	Parameters
21521	Grid forming operation	P- and Q-Droop	Classic GFM mode, as in previous releases. Inertia is now completely separated out of this mode.	DrpHz DrpVol
22321	Grid forming with angle inertia	P-Inertia and Q-Droop	New mode, requires Inertia Feature	InertiaThetaH InertiaHzDmp DrpVol
22322	Grid forming with amplitude inertia	P-Droop and Q-Inertia	New mode, requires Inertia Feature	DrpHz InertiaVolH InertiaVolDmp
22323	Grid forming with combined inertia	P- and Q-Inertia	New mode, requires Inertia Feature	InertiaThetaH InertiaHzDmp InertiaVolH InertiaVolDmp

The Mode **"P- and Q-Droop"** is the recommended mode for island systems and blackstart. It is equivalent to the previous standard mode of operation.

The Mode **"P-Inertia and Q-Droop"** is the recommended mode for grid-parallel operation with inertia. It is the mode that resembles a synchronous machine: inertia resembles the mechanical part, and terminal voltage control with droop characteristic resembles an AVR and the exciter winding. However, the slow dynamics of the AVR and exciter winding are not modeled, but instead a fast voltage control is implemented.

The Modes **"P-Droop and Q-Inertia"** and **"P- and Q-Inertia"** implement a Q-Inertia, or Voltage Amplitude Inertia behavior. This results in accurate following of reactive power setpoint with dynamics that resemble an inertia along the voltage amplitude axis. **The modes "P-Droop and Q-Inertia"** and **"P- and Q-Inertia" are experimental, and not recommended for production use.**

The new OpCmds including Inertia are only available with the Inertia Feature (Grid Forming Performance Package / Stability Pathfinder Package / Inertia Package).

2.4 Units and base ratings

The main parameters, their unit and the relevant base rating are given in the table below. Please note that changing the internal base rating parameters VARtg, WRtg and AmpRtg of the inverter is not supported, as it will impact on the control parameters. The only exception is the reactive power rating VArRtg: in case of full-circle reactive power operation it must be set equal to VARtg instead of 60% of VARtg.

	Channel Name	Unit	Base Rating
Droop-Mode			
Active	GriForm.AcCtl.DrpHz	Hz/pu	WRtg
Reactive	GriForm.AcCtl.DrpVol	-	VArRtg
Inertia-Mode			
Active	GriForm.AcCtl.InertiaThetaH	s	WRtg
Reactive	GriForm.AcCtl.InertiaVolH	s	VArRtg
Active	GriForm.AcCtl.InertiaHzDmp	Hz/pu	WRtg
Reactive	GriForm.AcCtl.InertiaVolDmp	-	VArRtg
All Modes			
Negative sequence	GriForm_AcCtl_DrpVolNs	-	VArRtg

2.5 Migration of Inertia Mode from R9 to R10

Inertia parameters are now completely separated from Droop parameters. New parameters are introduced, see column "Parameters" above and table below. The new OpCmds need to be used to activate inertia mode.

Remark: DrpHz and DrpVol were "dual-use" in R9, for P-Droop and P-Inertia mode. This ends now.

Comparison R9 vs R10 parameters regarding inertia:

	R9 (old)	R10 (new)	Parameter upgrade R9->R10
Inertia H constant	DrpThetaH	InertiaThetaH	set InertiaThetaH (R10) to the value of

			DrpThetaH (R9, inertia mode).
Inertia Damping	DrpHz	InertiaHzDmp	set InertiaHzDmp (R10) to the value of DrpHz (R9, inertia mode)

2.6 Switching between operation modes

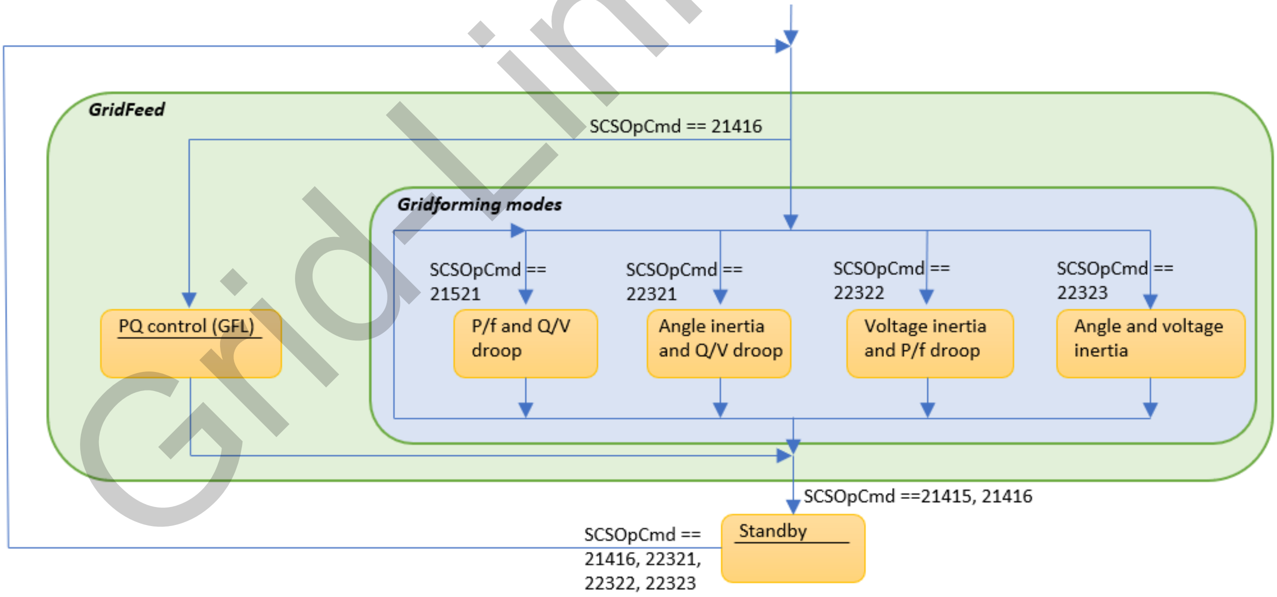
Switching between the grid forming operating modes (SCSOpCmds 21521, 22321, 22322, 22323) is possible during operation without interruption. While transients will occur, this allows an uninterrupted transitioning between modes.

This mode switching should only be used after careful analysis and understanding of the potential transients and related risks.

The intended use is for the transition between blackstart/island mode to grid-parallel operation with inertia. For Blackstart the "P- and Q-Droop" (SCSOpCmd=21521) mode is typically used. After a successful blackstart the plant may have to be switched to "P-Inertia and Q-Droop" (SCSOpCmd=22321) mode. Likewise, there may be situations where the plant shall be prepared for islanded operation. In that case the reverse transition from "P-Inertia and Q-Droop" mode to "P- and Q-Droop" mode can be used.

Switching from Gridforming to Gridfollowing modes is possible, but will involve an automatic transition through the Standby mode.

The below figure shows the possible transitions paths between operating modes.



The feedback register for operating state OpStt will, for all abovementioned grid forming modes give the feedback GriForm (21429).

3 Modbus parameter interface for grid forming parameter settings

3.1 Operating mode selection

Modbus Unit 2

Holding-Register

Modbus Address	Channel Name	Unique ID	Type	Scale	Offset	Rep.	Unit	Read / Write
2276	AuxCtl.SCSOpCmd	3960	U32	1	0	ENUM	-	RW

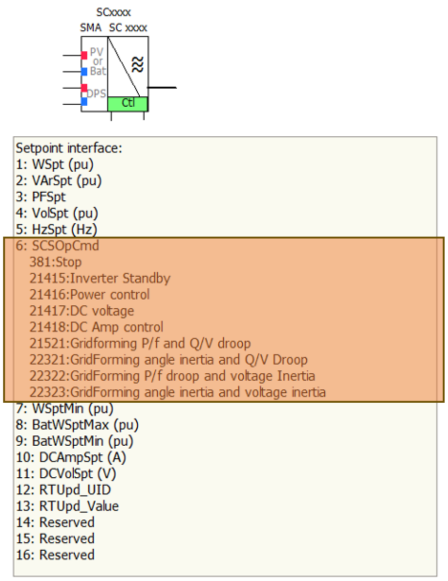
Mapping

Modbus Address	Channel Name	Unique ID	Return code	Related text
2276	AuxCtl.SCSOpCmd	3960	381	Stop
			2291	Battery standby
			21415	Inverter standby
			21416	Power control
			21417	DC voltage control
			21418	DC current control
			21454	QonDemand
			21521	Grid forming operation
			22321	Grid forming with angle inertia
			22322	Grid forming with amplitude inertia
			22323	Grid forming with combined inertia

3.2 PSCAD model: How to define operating mode

The operating mode is set via the "SCSOpCmd" input in the setpoint interface. The PSCAD model is using the same identifier numbers as stated in above Modbus table.

PSCAD:



3.3 Inertia and Droop parameter settings

Modbus parameters for Inertia and Damping parameters will not be activated instantly, but only with the next change of operation mode. This prevents undesired combinations of Inertia and Damping parameters to be activated.

Inertia and Droop parameters received from modbus will only be activated when the operating mode is changed

- from inertia mode to standby
- back from standby to inertia mode.

That is, after sending new setpoints, the OpCmd should be changed to Standby, then back to the desired Inertia OpCmd.

Example:

- Send new InertiaThetaH
- Send OpCmd = Standby
- Wait for GriForm.AcCtl.InertiaThetaHFb reports back the desired new value
- Send OpCmd = "P-Inertia and Q-Droop"

Modbus Unit 3

Holding-Register

Modbus Address	Channel Name	Unique ID	Type	Scale	Offset	Rep.	Unit	Read / Write
119	GriForm.AcCtl.DrpHz	7576	S16	1000	0	FIX3	Hz/pu	RW
120	GriForm.AcCtl.DrpVol	7577	S16	1000	0	FIX3	-	RW
–								
135	GriForm.AcCtl.InertiaThetaH	8909	S32	10000	0	FIX4	s	RW
137	GriForm.AcCtl.InertiaVolH	8917	S32	10000	0	FIX4	s	RW
139	GriForm.AcCtl.InertiaHzDmp	9194	S32	1000	0	FIX3	Hz/pu	RW

141	GriForm.AcCtl.InertiaVolDmp	9200	S32	1000	0	FIX3	-	RW

3.4 Feedback Info on "Input Register"

The "Input Register" provides feedback values from the inverter. The "Min/Max" values are hardcoded limits for the respective variables, and provided in feedback registers. The Min/Max limits are implemented to avoid invalid values. The "Fb" values provide the actual values as feedback, to be able to confirm/validate the sent reference values.

Example:

- Command written by plant controller:
    - GriForm.AcCtl.InertiaThetaH = 2s
- Feedback values available for plant controller:
    - InertiaThetaHMin : minimum permitted value, H=1s
    - InertiaThetaHMax : maximum permitted value, H=25s
    - InertiaThetaHFb : actual value, e.g. H=2s

The (OpStt) feedback will, for all grid forming modes (all four OpCmds for Gridforming modes, see Section 2.3), give the same feedback GridForm (21429). See the Technical Information Modbus Interface for Sunny Central Storage for more information.

Input-Register

Modbus Address	Channel Name	Unique ID	Type	Scale	Offset	Rep	Unit	Read / Write
98	OpStt	332	S32	1	0	ENUM	-	R
280	GriForm.OvAmpStt	8969	U32	1	0	ENUM	-	R
282	GriForm.OvAmp.AmpMaxFrtAval	8970	S32	10000	0	FIX4	pu	R
284	GriForm.OvAmp.AmpMaxAval	8971	S32	10000	0	FIX4	pu	R
–								
306	GriForm.AcCtl.InertiaThetaHMin	9186	S32	10000	0	FIX4	s	R
308	GriForm.AcCtl.InertiaThetaHMax	9188	S32	10000	0	FIX4	s	R
310	GriForm.AcCtl.InertiaVolHMin	9190	S32	10000	0	FIX4	s	R
312	GriForm.AcCtl.InertiaVolHMax	9192	S32	10000	0	FIX4	s	R
314	GriForm.AcCtl.InertiaHzDmpMin	9196	S32	1000	0	FIX3	Hz/pu	R
316	GriForm.AcCtl.InertiaHzDmpMax	9198	S32	1000	0	FIX3	Hz/pu	R
318	GriForm.AcCtl.InertiaVolDmpMin	9202	S32	1000	0	FIX3	-	R
320	GriForm.AcCtl.InertiaVolDmpMax	9204	S32	1000	0	FIX3	-	R
322	GriForm.AcCtl.InertiaThetaHFb	9210	S32	10000	0	FIX4	s	R
324	GriForm.AcCtl.InertiaVolHFb	9211	S32	10000	0	FIX4	s	R
326	GriForm.AcCtl.InertiaHzDmpFb	9212	S32	1000	0	FIX3	Hz/pu	R
328	GriForm.AcCtl.InertiaVolDmpFb	9213	S32	1000	0	FIX3	-	R

3.5 Current Boost Status feedback GriForm.OvAmpStt

The feedback values include the state of the current boost, see the mapping below:

Mapping

Modbus Address	Channel Name	Unique ID	Return code	Related text	Comment	Example
280	GriForm.OvAmpStt	8969	800	Disabled	Boost disabled	Boost is not activated in a non-boost plant
			885	None	Boost not available after event	5 second inertia event happened, recovery phase ongoing (temperature and "long" timer)
			2630	Normal	Boost fully available	Precondition for boost is fulfilled
			22221	Short	Boost for FRT available (first sector only)	After event: partial recovery completed; first sector for FRT event available (140ms), but not full boost (5s)

4 FRT Modes and Configuration

The FRT mode in grid forming mode is defined by parameter GriForm.Frt.Mod (PSCAD: GriForm_Frt_Mod). The available modes are:

- Disabled (GRIFORM_FRT_MOD_DISABLE)
- Full Virtual Impedance (GRIFORM_FRT_MOD_FULL_VI)
- k-factor Basic (GRIFORM_FRT_MOD_FULL_VI_K_FAC_BASIC)
- k-factor Advanced (GRIFORM_FRT_MOD_FULL_VI_K_FAC_ADVANCED).

The mode “Disabled” must not be used and is only available for legacy compatibility.
The mode “Full Virtual Impedance” aims at limiting current with a virtual impedance. The current will be limited at the maximum permitted value. Reactive current is prioritized, i.e. active current will be reduced first.
The modes “k-factor Basic” and “k-factor Advanced” will use a virtual impedance to establish a k-factor characteristic (and limit the current). Reactive current priority can be switched on and off.

4.1 Full Virtual Impedance

In case of excessive current on one of the three phases, the virtual impedance control will be enabled. The virtual impedance control limits the apparent current at nominal current. Reactive current is prioritized, i.e. active current will be reduced first. The Initial value of maximum short circuit current in the virtual impedance may overshoot.
This mode is recommended for UK Stability Pathfinder 2 plants and backwards-compatible to software release R9.

4.2 FRT with k-factor characteristic

The k-factor characteristic as defined in most grid-connection codes for inverter-based plants establishes a proportional relation between voltage step magnitude and reactive current:

$$\Delta i_Q = -\, k \cdot \Delta v \,.$$

The k-factor behavior is replicated in grid-forming mode through applying the virtual impedance. The factor is defined for positive sequence and negative sequence separately.

The two FRT modes with k-factor characteristic are different regarding parametrization:

1. K-factor Basic mode will define the k-factors directly (2 parameters)
    a. GriForm.KFacPs
    b. GriForm.KFacNs
2. K-factor Advanced mode will define virtual impedance values instead (5 parameters, see detailed explanation below).

In both modes, the fault current will be either an inherent current (no priority for active or reactive), or reactive current can be prioritized. This is selected through the parameter

GriForm.Frt.AmpPsQPrioEna .

4.2.1 Basic mode parametrization

GriForm.KFacPs and GriForm.KFacNs describe the positive and negative sequence k-factors. These can be defined in k≥2. The internal impedance parameters and Q-droop parameters will be derived automatically.

The Q-droop parameter (reactive power/voltage droop parameter) for normal operation GriForm.AcCtl.DrpVol cannot be changed in Basic mode (values sent via modbus will be ignored).

4.2.2 Advanced mode parametrization

k-factors and Virtual Impedance values.

The k-factor defines the factor between voltage and reactive current:

$$k = \frac{\Delta i_Q}{\Delta v}.$$

The reciprocal of the k-factor is an impedance value:

$$z = \frac{\Delta v}{\Delta i_Q}.$$

All parameters are defined as (virtual) impedance values, and are therefore reciprocals of k-factors.

k-factor	2	4	6	20
Impedance	0.5	0.25	0.167	0.05

The impedance parameters that define the k-factor in FRT mode characteristics should be defined manually:

Parameter	Value	Comment
GriForm_Frt_VirtImpReact	0.167 (set to reciprocal of desired k-factor)	Virtual impedance, positive sequence reactance
GriForm_Frt_VirtImpReactMin	0.167 (shall be set to same value as VirtImpReact)	Virtual impedance, positive sequence minimum reactance
GriForm_Frt_VirtImpReactNs	0.167 (set to reciprocal of desired k-factor)	Virtual impedance, negative sequence reactance

Shallow faults – voltage steps within normal operation range

In addition to the FRT mode parameters, to obtain the k-factor behavior also for **shallow faults**, the Q-droop parameters shall be set get the same behavior as from virtual impedance. This requires a re-scaling due to the different per-unit base of Q-droops and the virtual impedance in fault mode (related to pre-R10 legacy compatibility).

The per-unit base values relevant for impedance values and droop factors need to be considered:

DrpVolNs	**VArRtg**
DrpVol	**VArRtg**
GriForm_Frt_VirtImpReact	VARtg
GriForm_Frt_VirtImpReactMin	VARtg
GriForm_Frt_VirtImpReactNs	VARtg

Due to the different ratings, to get the same behavior the factor $\frac{VArRtg}{VARtg}$ must be considered.

k-factor	2	4	6	20
Impedance	0.5	0.25	0.167	0.05
Q-droop (for VArRtg = 60% of VARtg, default)	0.3	0.15	0.1	0.03
Q-droop (for VArRtg = VARtg, project specific extended Q-range)	0.5	0.25	0.167	0.05

Parameter	Value	Comment
GriForm_AcCtl_DrpVol	0.1 (set to $\frac{VArRtg}{VARtg}$ *GriForm_Frt_VirtImpReact) **See above regarding scaling.**	Droop: Reactive Current – Voltage Droop positive sequence; only active for ScsOpCmd = 21521 or 22321
GriForm_AcCtl_DrpVolNs	0.1 (set to $\frac{VArRtg}{VARtg}$ *GriForm_Frt_VirtImpReact) **See above regarding scaling.**	Droop: Negative sequence droop; active for ScsOpCmd = 21521/22321/22322/22323

Reasonable k-factor ranges

The k-factor can be adjusted in the range of 2 to 6 and above. Typical values are 6 and above. For values below 4, the behavior will be like a "soft" voltage source. It is recommended to use equivalent k-factor of 6 or higher.

Especially in normal operation (and shallow faults) the typical k-factors in the range of 2 to 6 are significantly different from typical Q-Droop values:

- The recommended (default) value for voltage droop DrpVol and negative sequence voltage droop DrpVolNs is 0.03, equivalent to k=20 (for a VArRtg of 60% of VARtg).

If instability occurs for low k-factor values (potentially for k<3, depending on grid impedance), the parameters

- GriForm.AmpQfilTm und GriForm.AmpNsDQFilTm can be set to 0.02s (instead of 0.01s)
- GriForm.AmpDfilTm should not be changed (0.01s).

5 Power limitation

5.1 Limitation of P and Q related to thermal derating

Prioritization of active and reactive power, both in positive and negative sequence, can be parametrized by

- VADrtPriMod – Active or Reactive power priority (W oder Var)
- GriForm.AcCtl.PriModPsRelEna – Positive sequence relative prioritization (Disable/Enable)

The active and Reactive Power prioritization can be set via the parameter VADrtPriMod, selectable is VADRTPRIMOD_W for active power prioritization and VADRTPRIMOD_VAR for reactive power prioritization. The Positive sequence relative prioritization can be activated via the parameter GriForm.AcCtl.PriModPsRelEna.

Active Power prioritization

In this mode the active Power will be prioritized when the inverter is in derating. The negative sequence takes precedence over the positive sequence. Accordingly, in the case of current derating, first the reactive power in the positive sequence, then the active power in the positive sequence, then the reactive power in the negative sequence is reduced and finally the active power in the negative sequence.

Reactive Power prioritization

In this mode the reactive Power will be prioritized when the inverter is in derating. The negative sequence takes precedence over the positive sequence. Accordingly, in the case of current derating, first the active power in the positive sequence, then the reactive power in the positive sequence, then the active power in the negative sequence is reduced and finally the reactive power in the negative sequence.

Positive sequence relative prioritization

In this mode also the negative sequence takes precedence over the positive sequence. In the negative sequence the reactive power is prioritized over the active power. In the positive sequence, active and reactive power are reduced in the same proportion. The basis for this is the actual measured active and reactive power ratio in the positive sequence. During derating, the ratio can change if the influence of the power reduction is different, such as in the case of an island grid.

5.2 Transient limitation related to AC current and DC current and voltage limits

If necessary, the dynamics of the active and reactive AC current limitation control loops can be tuned by altering the following parameters. Due to different dynamics in “P-Droop” vs. “P-Inertia” GFM operating modes, independent sets of parameters have been implemented.

The limitation consists of PI controllers that become active in case a limit is exceeded.

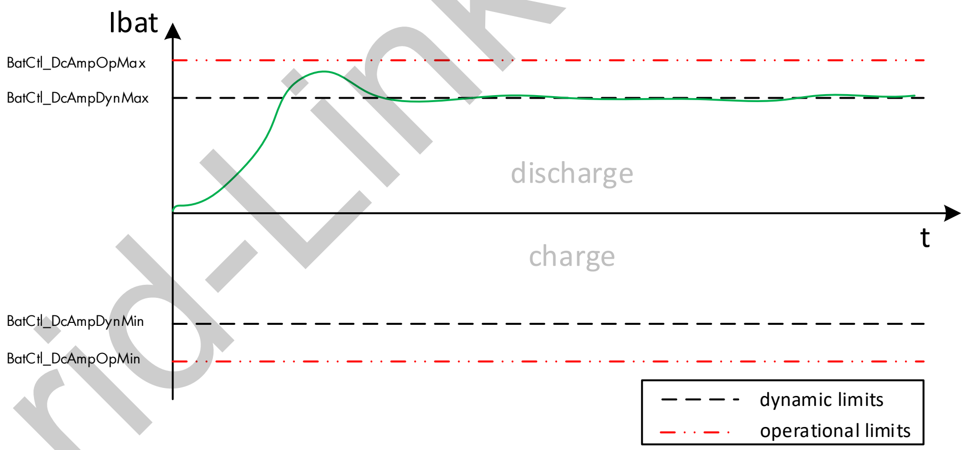
5.2.1 AC current limitation

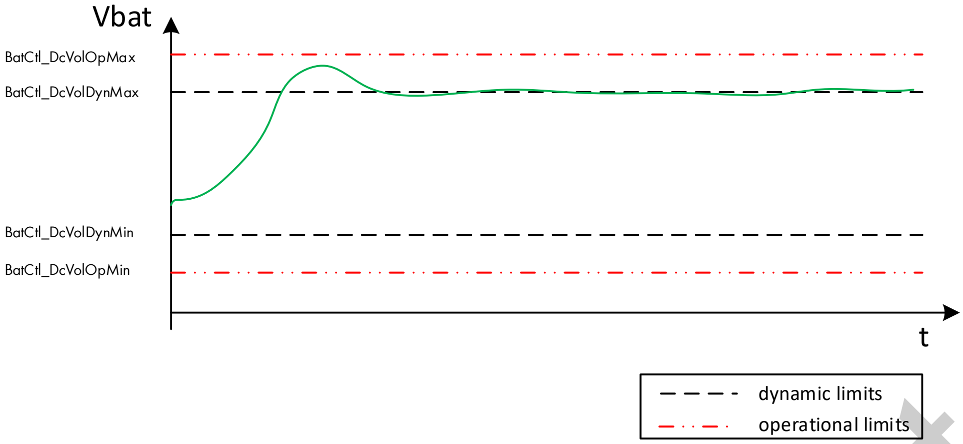
For AC side limitation, a PI controller compares the current magnitude with the permitted maximum current magnitude. The maximum allowed currents (AmpPsDMax, AmpPsQMax, AmpNsDMax, AmpNsQMax) used for AC current limitation control is determined based on the selected active and reactive current priorization mode (as explained in Section 5.1).

	GFM P-Droop	GFM P-Inertia
AC current limitation		
proportional gain direct axis	GriForm.AcCtl.AmpDLimKp (0.6)	GriForm.AcCtl.InertiaAmpDLimKp (0.6)
integral gain direct axis	GriForm.AcCtl.AmpDLimKi (22.5)	GriForm.AcCtl.InertiaAmpDLimKi (22.5)
proportional gain quadrature axis	GriForm.AcCtl.AmpQLimKp (2.4)	GriForm.AcCtl.InertiaAmpQLimKp (2.4)
integral gain quadrature axis	GriForm.AcCtl.AmpQLimKi (90)	GriForm.AcCtl.InertiaAmpQLimKi (90)

5.2.2 DC current and voltage limitation

To dynamically keep the DC current and voltage within given ranges respective controllers have been implemented. Again, the parameters are split according to the corresponding GridForming control modes. The battery limits can be set in the inverter via the inverters Modbus interface (see chapter "Battery Communication" in the Technical Information document "Modbus Interface for Sunny Central Storage").





	GFM P-Droop	GFM P-Inertia
DC current limitation		
proportional gain	GriForm.DcCtl.AmpKp (0)	GriForm.DcCtl.InertiaAmpKp (0)
integral gain	GriForm.DcCtl.AmpKi (5)	GriForm.DcCtl.InertiaAmpKi (20)
DC voltage limitation		
proportional gain	GriForm.DcCtl.VolKp (0)	GriForm.DcCtl.InertiaVolKp (0)
integral gain	GriForm.DcCtl.VolKi (30)	GriForm.DcCtl.InertiaVolKi (60)

6 Harmonics and negative sequence behavior

6.1 Harmonics

Harmonics controllers are available in SCS UP(XT) to reduce harmonic currents in different orders. The standard configuration for grid-following operation is active reduction of 0^{th}(DC), 2^{nd},4^{th} ,5^{th} harmonic currents.

For grid-forming in grid-parallel operation, the recommended configuration is to enable the harmonic controllers:

1. standard settings should not be changed - (identical to grid-following - 0^{th}(DC), 2^{nd},4^{th} ,5^{th}).
2. General enable parameter to activate harmonic controller in grid forming modes:
    a. GriForm.AcCtl.HarmCtlEna : Enabled.
    b. Please note that this parameter is by default set do Disabled.

In this configuration, the same measurements as for grid-following mode can be applied for harmonic studies. Harmonics are highly sensitive to the grid situation.

For Microgrids, the harmonic configuration should be reviewed individually before enabling the harmonic controller.

R10 is expected to behave largely the same as R9, but the configuration of harmonic control should be verified.

6.2 Negative sequence behavior

The voltage-source behavior of grid forming control causes the inverter to balance the voltage, and will allow asymmetric currents. The negative sequence behavior in can be influenced by the negative sequence droop setting (GriForm.AcCtl.DrpVolNs). This behaves like a negative sequence reactance, i.e. it will make the voltage source more “soft” and allow some voltage distortion at the inverter terminals. However, it is not possible to completely surpress negative sequence currents in grid forming mode. This is the intended behavior and it needs consideration for plant operation:

Current asymmetry means that the (apparent or instantaneous) currents differs between the three phases. As the current is limited to the current rating in each phase, any asymmetry will prevent the inverter from feeding it’s rated apparent power to the grid.

In grid-following inverters, in contrast, the current is controlled to be symmetric, and this allows feeding full power even to a grid connection with pre-existing negative sequence voltage distortion.

The inverter in GFM mode in asymmetric grid conditions will begin to de-rate earlier than a grid-following inverter.

7 Misc

7.1 Testing of protection settings with test terminal strips

Field testing of protection settings through test terminal strips with external protection test device is not possible in GFM mode (e.g. introduce external test signal for frequency or voltage deviations). To test the protection settings with test terminal strips in the field, the inverter needs to be operated in grid-following mode (Power Control OpCmd).

The protection functions for voltage and frequency protection are identical in Power Control and Grid Forming Control Modes.

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