Technical Information

Grid Forming with SUNNY CENTRAL STORAGE

ENGLISH CONFIDENTIAL GridFormingSCS-TI-en-12 | Version 1.2

Revision History

Document-Number	Version and Alteration Review [1])		Comments	Author
-1:YE262018	1.0	A	First Edition	M. Mostafa
-1:YE432018	1.1	A	Revisions	C. Hardt
-1:YE382019	1.2	A	Revisions, update for SW rel 6	T. Stocker
-1:YE222020	1.2.1	A	Small Revisions	T. Stocker

[1]) A: Alterations due to faulty documents or improvement of the documentation

B: Alterations maintaining full or upward compatibility

C: Alterations limiting or excluding compatibility

1 Introduction

Feeding in power into an established grid is the state of the art of almost all grid-tied inverters. The grid-tied inverters require stable grid (voltage and frequency boundaries) to operate with. The main purpose of such inverters is to feed-in without disturbance.

The grid forming inverter acts differently and does not require a grid to operate; they can establish their own grid, i.e. creating stable voltage and frequency. Such an operation mode is essential for running an island grid fully on renewable and energy storage system without the need for running generators (mostly diesel genset or gas motors) to establish the grid and by that maximizing the renewable share in the energy generation. On public grid such a feature is needed for work with very weak grid and to provide blackstart for large power plant.

1.1 Validity of the Document

This document is valid for the following devices for the hardware version B1 and above:

- SCS 1900
- SCS 2200 (-US)
- SCS 2475 (-US)
- SCS 2900 (-US)
- SCS 2300 UP-XT (-US)
- SCS 2400 UP-XT (-US)
- SCS 2530 UP-XT (-US)
- SCS 2630 UP-XT (-US)
- SCS 3450 UP (-US)
- SCS 3600 UP (-US)
- SCS 3800 UP (-US)
- SCS 3950 UP (-US)
- SCS 3450 UP-XT (-US)
- SCS 3600 UP-XT (-US)
- SCS 3800 UP-XT (-US)
- SCS 3950 UP-XT (-US)

This document is also only valid for inverters with software version 6.xx.xx.R and above.

1.2 Overview of Operation Modes of SCS

SCS has two operation modes regarding AC side control, current control and voltage control. The SW for grid forming is activated only if the corresponding option is bought. It is a cost related option. Auxiliary supply is also critical for blackstart operation so external aux supply must be selected for blackstart applications. The following options exist in the configuration of SCS:

Grid Forming

0 – No Grid Forming	Only Grid Tied mode is possible
1 – Grid Forming	Grid Tied and Grid Forming are possible to select over Modbus

2 – Grid Forming with DC Precharge	Same as option 1 plus DC-precharge hardware This is needed for blackstart.
3 – No Grid Forming with DC Precharge	Same as option 0 plus DC-precharge hardware Includes hardware necessary for blackstart use later on.

Auxiliary supply

0 – Internal	Use internal aux transformer
1 – External *	Customer provided 3-phase 230/400 VAC power

*single-phase critical loads aux supply ordered via Special Version. Planned for future HW release.

Externally, i.e. installation dimensions, and usability of the inverter, the SCS is the same regardless of the options related to grid forming functions.

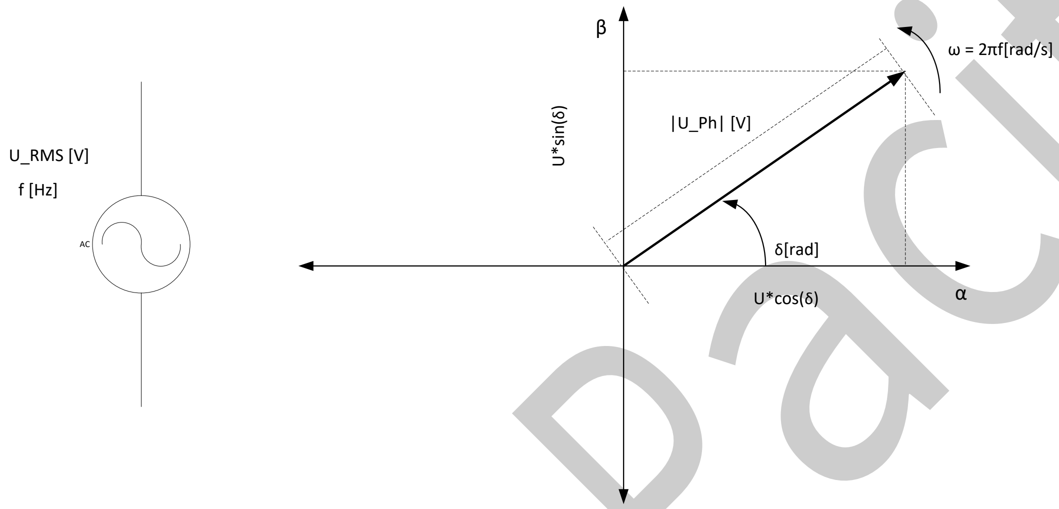
Here is an overview of the main differences between the two basic operation modes.

Current Control Mode	Voltage Control Mode
A grid tied inverter operates as a current source to achieve the requested active power and reactive power set points. The inverter needs to always have a grid voltage established by other generators to synchronize to and feed-in or draw power from the grid. In this mode, the inverter has full control over its current wave form (amplitude and angle). The inverter can achieve the requested set-points faster since it controls the current directly. In case of FRT conditions, the inverter can set its current to the requested values as per the grid codes.	A grid forming inverter operates as voltage source device to control the voltage and frequency. The inverter can work in parallel with other generators or in stand-alone mode. In this mode, it can also control the active power and reactive power based on given set-points. Not by controlling the current but by directly adjusting the output voltage amplitude and angle (similar to synchronous generators). In case of FRT conditions, the inverter can only limit the current magnitude but not the angle.

2 Grid Forming using Sunny Central Storage

2.1 Basic Principle

In order to operate in grid forming mode, the inverter needs to generate a 3-phase voltage source. It uses the Voltage and Frequency as set-points to generate the needed 3-phase voltages. The diagram below shows the basic idea. The inverter control uses the simple parameters V & f to generate a two AC values in **αβ** coordinates, which then will be transferred to 3Ph **abc**-coordinates. This is valid due to the fact that on the LV side there are **no zero-sequence components**.



As it can be seen, in such a case, there is no current control. The current will be defined by the load.

The schematic on the right side shows an illustrative diagram of an island using gensets, PV, and battery system to serve the island load.

The load seen by the grid forming inverter can be calculated as following:

$$P_{inv} = P_{Load} - P_{Genset} - P_{PV}$$

The **system design and control** shall make sure that the resulting power on the inverter will exceed neither the inverter power nor the battery power.

Only using a static voltage control scheme is not sufficient for stable operation between multiple inverters and in parallel with grid or gensets. Therefore, droop functions should be implemented to adjust the voltage and frequency for stable operation and automatic load sharing between devices.

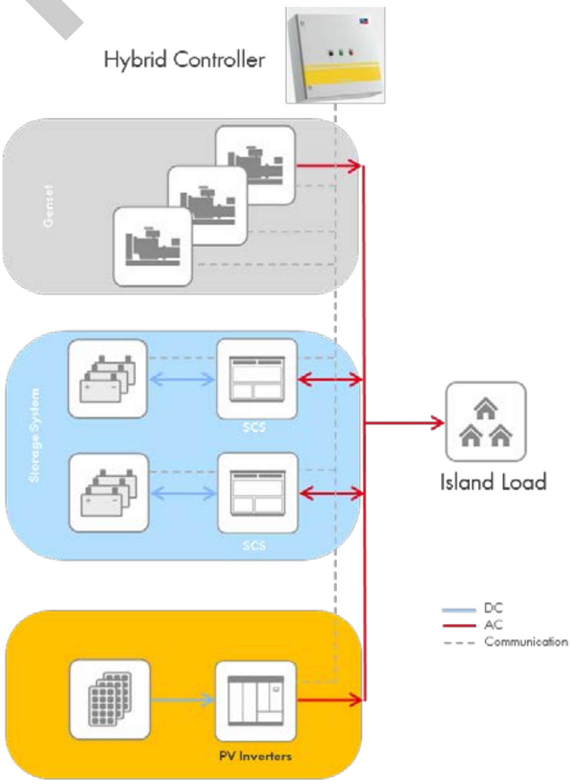


Figure 2.1 Overview Island Electricity Supply

2.2 Inverter Control Structure

In the previous section we see that V and f are needed to calculate the 3-phase voltage source. In this section we explain how V and f are calculated.

The inverter uses droop functions to calculate the f and V based on the active power and reactive power, respectively. The droops are emulating the behavior of a rotating machine by reducing the frequency when loaded with active power, and vice versa and reducing the voltage when loaded with reactive power and vice versa.

This will give similar behavior of the generators and allows parallel operation with generators without the need to fully reflect its dynamics.

The simplified equation looks like the following:

$$f = f_{ref} + kP * (P_{ref} - P_{inst})$$

$$V = V_{ref} + kQ * (Q_{ref} - Q_{inst})$$

where:

f_{ref}	is the defined target frequency at the reference power loading of the inverter
V_{ref}	is the defined target voltage at the reference reactive power loading of the inverter
P_{ref}	is the reference active power, at which the inverter shall generate the reference frequency
Q_{ref}	is the reference reactive active power, at which the inverter shall generate the reference voltage
P_{inst}	is the measured power at the inverter level
Q_{inst}	is the measured reactive power at the inverter level
f	is the frequency the inverter will apply at the inverter level
V	is the voltage the inverter will apply at the inverter level
kP	is the droop gain of frequency df/dP
kQ	is the droop gain of voltage dV/dQ

Putting the two calculation steps in one graph will result the control structure shown in the figure below.

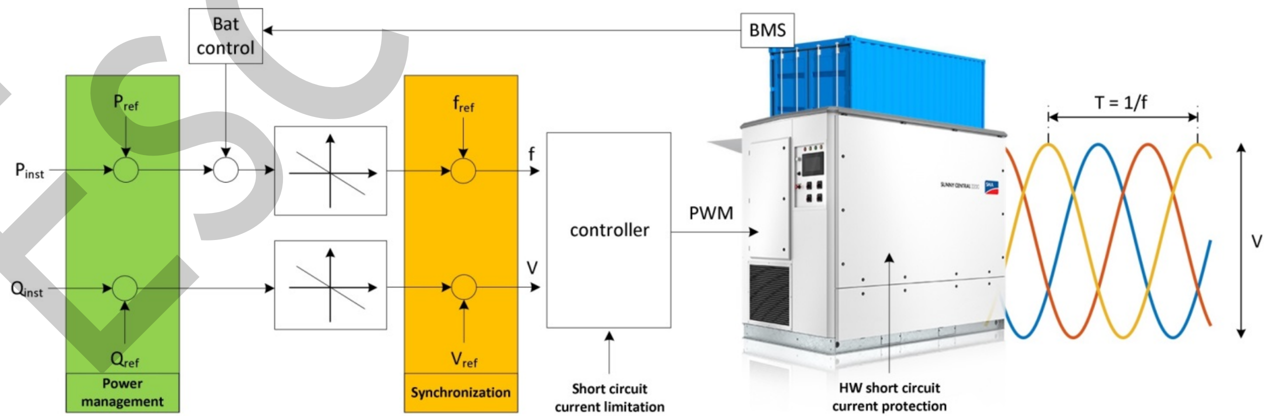


Figure 2.2 Overview of the voltage source control structure.

2.2.1 Active Power Droop

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 per Nominal Output. Default setting is -1 Hz 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 meant to be setup at commissioning and is usually 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 nominal frequency or by adjusting the power 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.

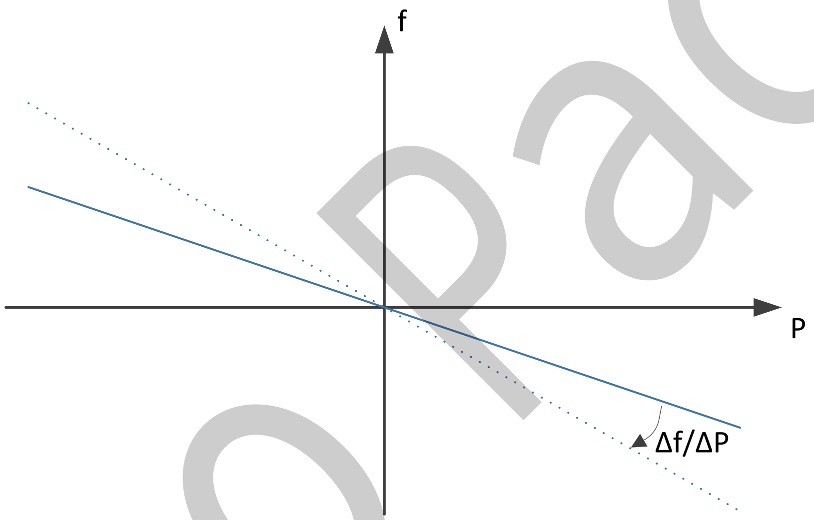


Figure 2.3 Active Power Droop, slope adjustment

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 parallel with a voltage source with the same nominal frequency set in that inverter, as indicated with Point A in Figure 2.4.

If there is no load or energy source in parallel, the power output will not meet the setpoint, but the frequency will be changed according the slope setting, example indicated as Point B in Figure 2.4.

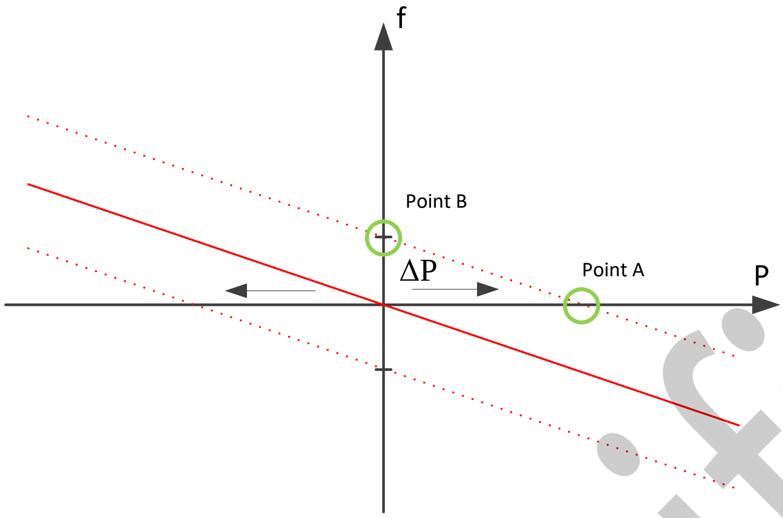


Figure 2.4 Active Power Droop, operational adjustment by using active power setpoint

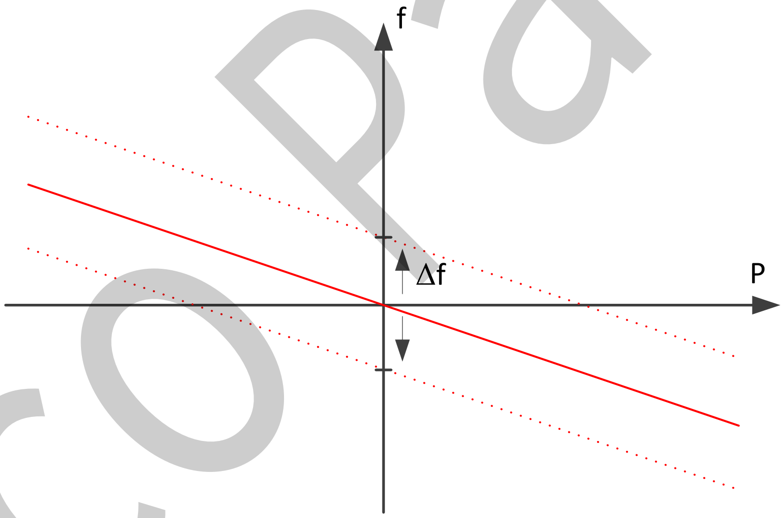


Figure 2.5 Active Power Droop, operational adjustment by using frequency adjustment

2.2.2 Reactive Power Droop

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. 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 meant to be 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 nominal voltage or by adjusting the reactive power 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.

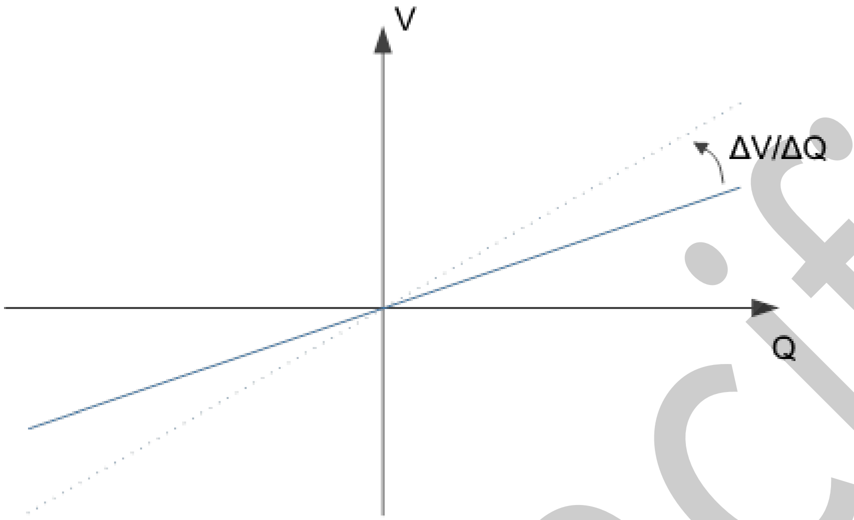


Figure 2.6 Reactive Power Droop, slope adjustments

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 setpoint only if the inverter operates in parallel with a voltage source with the same nominal voltage set in that inverter, as indicated with Point A in Figure 2.7

If there is no load or energy source in parallel, the power output will not meet the setpoint, but the voltage will be changed according to the slope setting, example indicated as Point B in Figure 2.7.

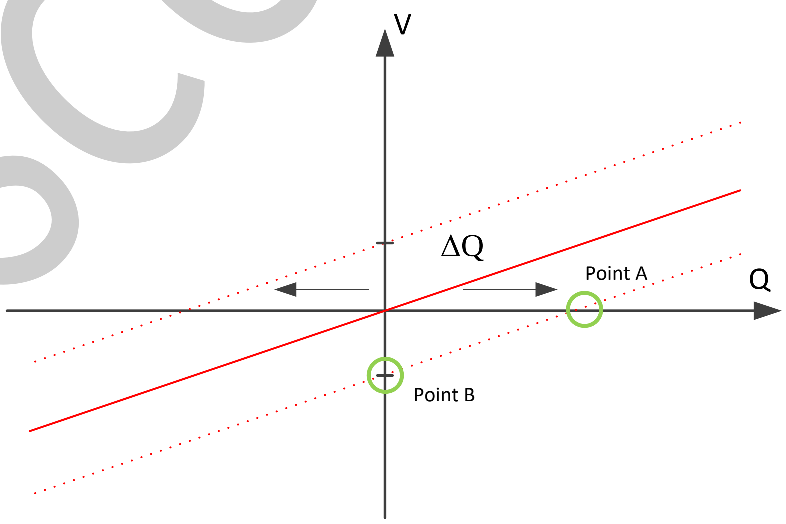


Figure 2.7 Reactive Power Droop, operational adjustements by using reactive power setpoint

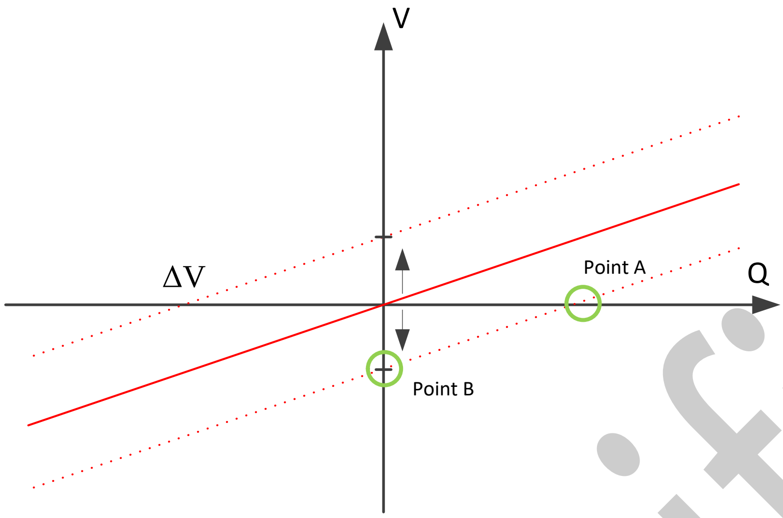


Figure 2.8: Reactive Power Droop, operational adjustments by using nominal voltage setpoint

2.2.3 Parallel Operation of multiple SCS

When connecting multiple inverters in grid forming mode in parallel to serve a joint load, they will share the load as per the setting of the droop equations. The basic concept is that at steady state situation, the frequency is the same across the grid. The load each SCS will see at this case can be illustrated by the schematic below.

How to set the load sharing differently? Two possible ways can be considered:

- If the slopes of the droops are set differently, or
- If the P_ref set at different values as shown in the previous sections.

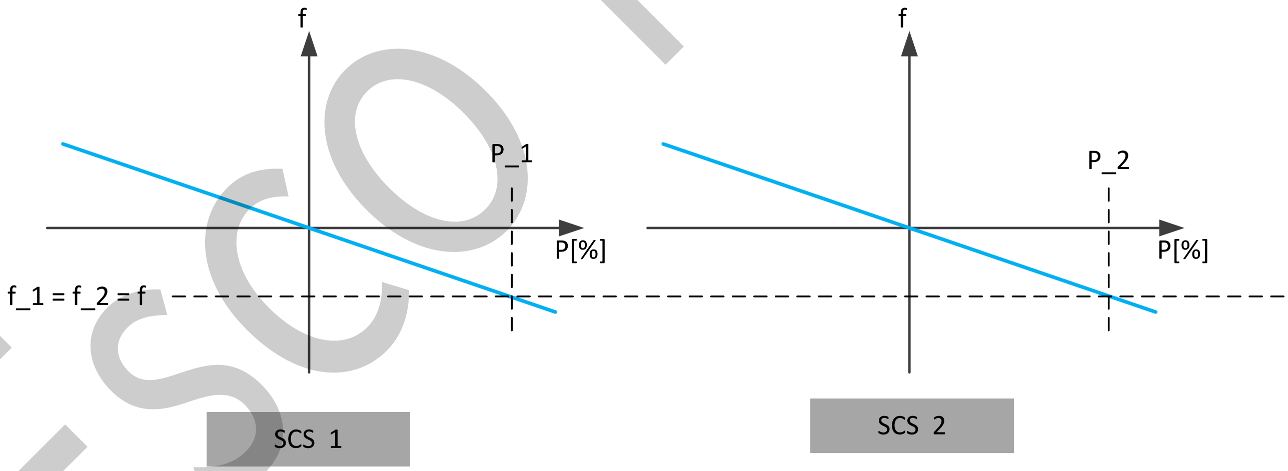


Figure 2.9: Load sharing between multiple SCS using same parameters

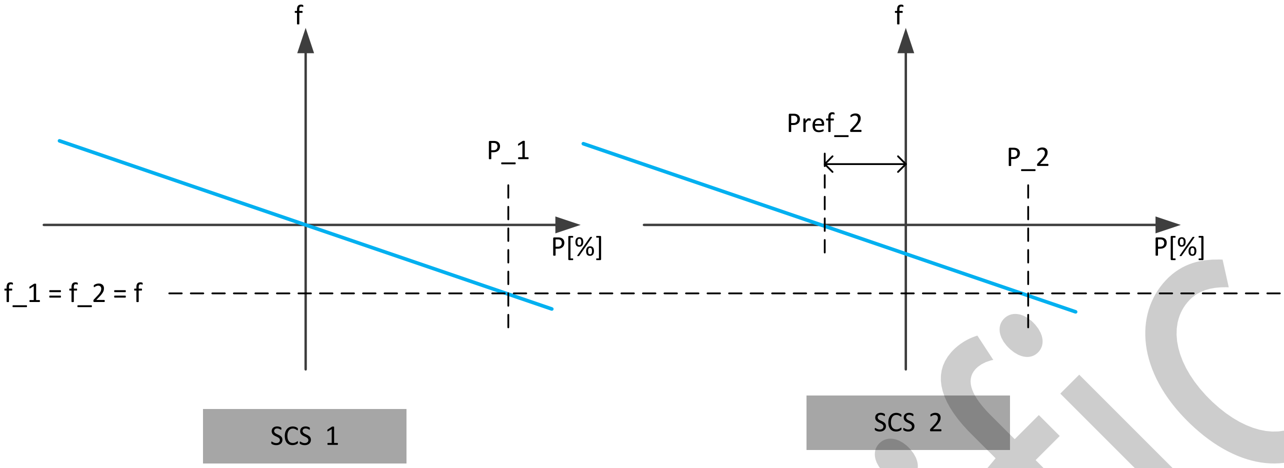


Figure 2.10: Load sharing between multiple SCS using different **Pref** parameters

2.3 Special Consideration and Device Capabilities

2.3.1 Behavior of inverter in case of grid fault

In case of a grid fault the inverter will immediately provide a current depending on the impedance of the fault in order to trip protection devices. If this fault current contribution exceeds the capabilities of the hardware a special current limitation mode is being activated.

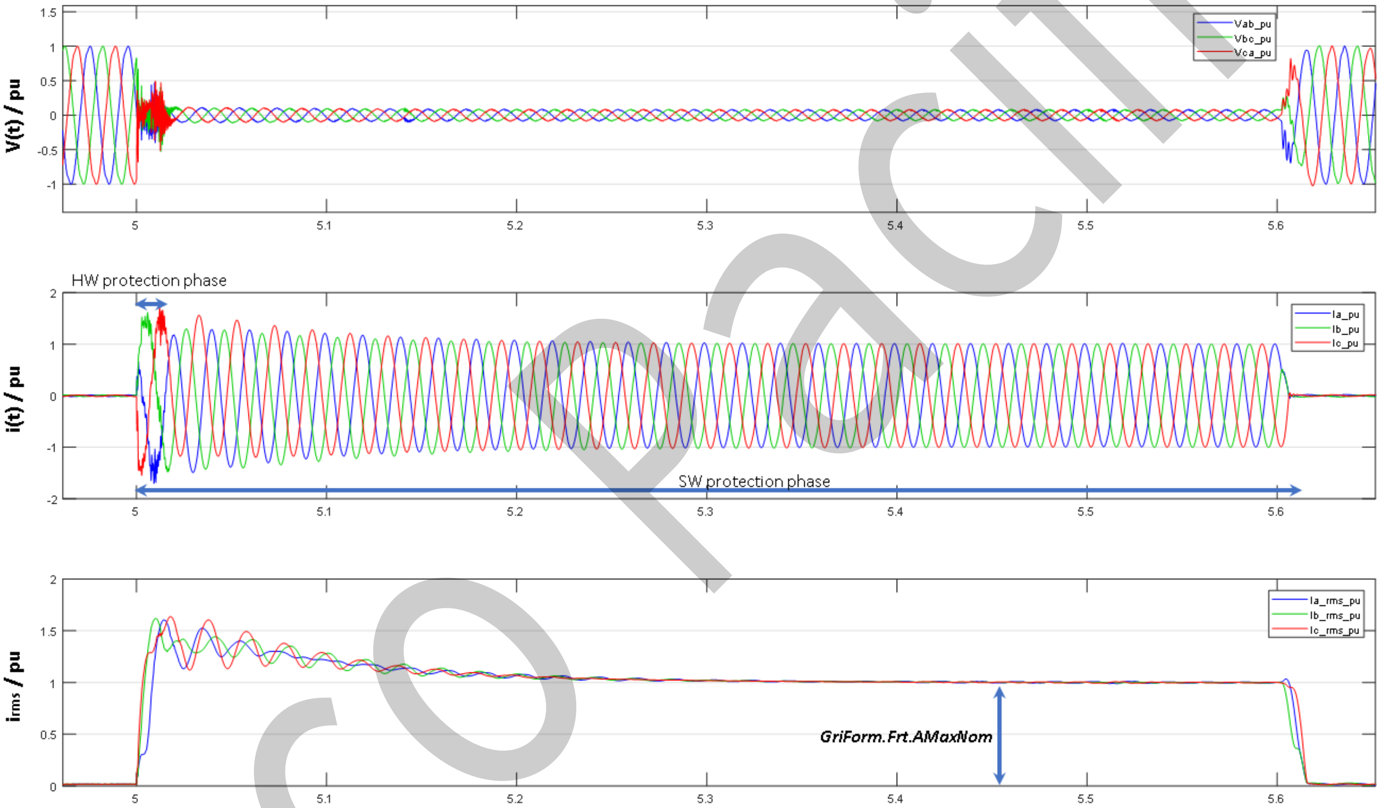


Figure 2.11 Example of inverter behavior during a 3-phase grid fault

As shown in Figure 2.11, current is provided during a 3-phase grid fault. At time t = 5.0 s the fault started, current is provided immediately.

In the first phase, the current is only limited by hardware protection means. Therefore, it is ensured to provide as high currents as possible and to protect the semiconductors from physical damage.

As shown below in Figure 2.12, the current provided during the first phase of the event, when the hardware protection is actually limiting the current, is not sinusoidal and the current is cut off at a certain level.

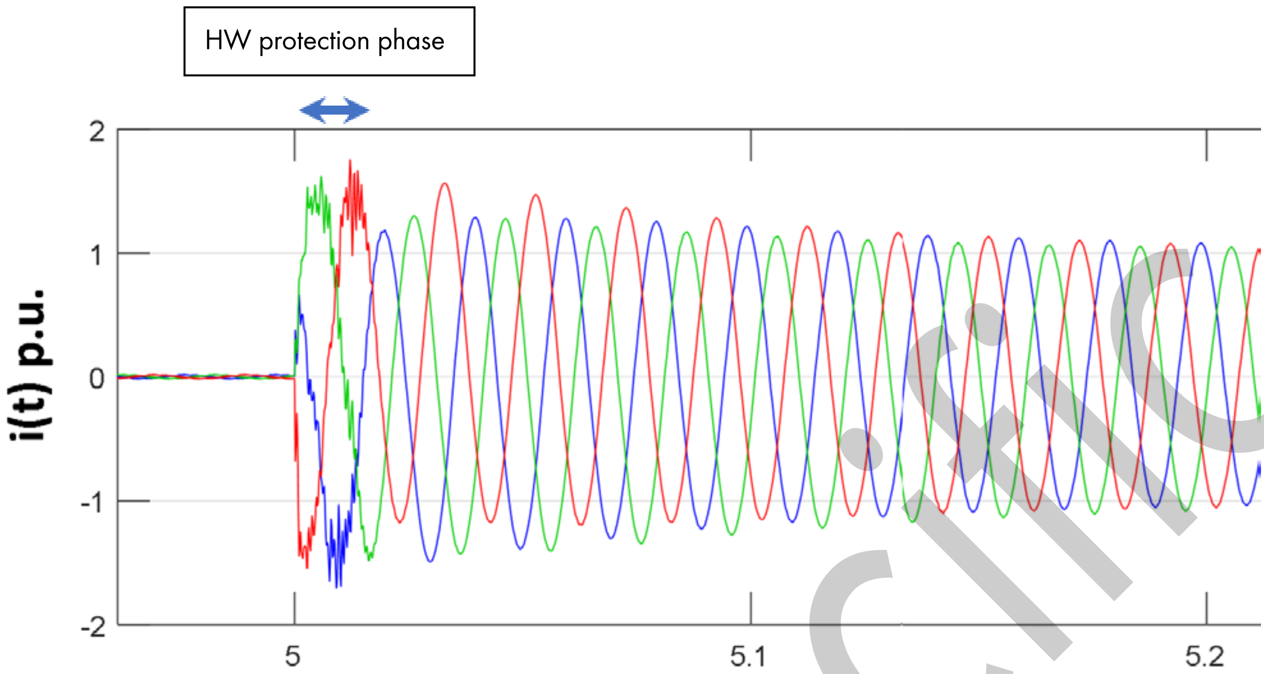


Figure 2.12 current waveform during active hardware protection phase

In order not to stress the semiconductors too long it is a goal to leave the HW protection phase as quickly as possible. Therefor a SW protection called "Virtual Impedance (VI)-mode" will adjust the voltage control setpoints to provide high current but to operate without triggering the hardware protection. The VI-mode gets activated once the current hits the hardware protection limit. In VI-mode the inverter emulates by means of software an additional impedance at its terminals. This impedance acts as a current limiting device. In above case the goal is to limit the steady state fault current to a predefined value of *GriForm.Frt.AMaxNom = 1.0 p.u.*. By constantly adapting the values of the virtual impedance the algorithm is reducing a too high current contribution until it settles at *GriForm.Frt.AMaxNom*.

In the shown measurements in Figure 2.12, the current is provided without cut-offs after about 1 cycle at 50 Hz or approximately 20 ms. The duration spent in the HW protection phase depends on the parameterization of the initial virtual impedance values.

As shown in Figure 2.13 the current during the SW protection phase is sinusoidal since there are no interferences of the hardware protection. The amount of current provided during the VI-mode can be parametrized; default setting is 1.0 p.u. as shown in Figure 2.13.

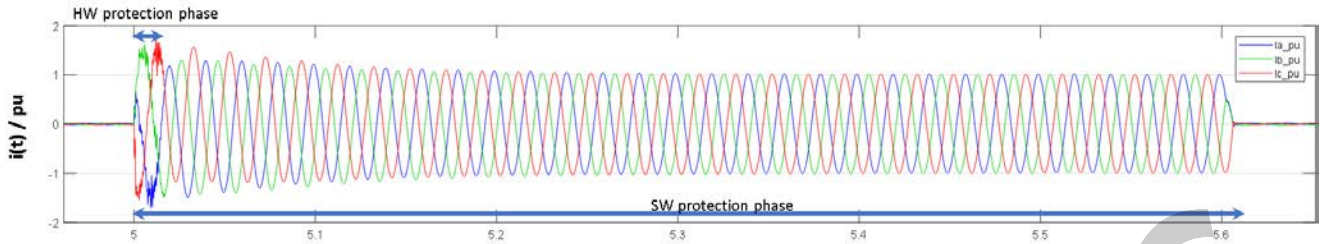


Figure 2.13 current waveform during software protection phase

The maximum duration of the software protection phase is dependent on parameter settings, decided upon the active time of the VI-mode for the voltage setpoint adjustments. Default setting is *GriForm.Frt.VirtImpLimTm* = 5s. Please consider lowering this value according to your needs.

Even during a grid fault situation, the voltage trip limits are still active, e.g. if an undervoltage limit is set to 80% for 0.5s , this will also limit the maximum time of current provision into a grid short circuit since the grid voltage can't be maintained at nominal voltage.

If the grid fault is cleared, the inverter will bring the voltage back to nominal operation. In the above shown case, where the SW Limit became active, the voltage returns to the nominal operating range, as soon as the current drops. In Figure 2.14, a voltage recovery is shown. The grid fault is cleared at t = 5.6 s, the voltage starts to rise immediately and reaches the nominal value within a few cycles.

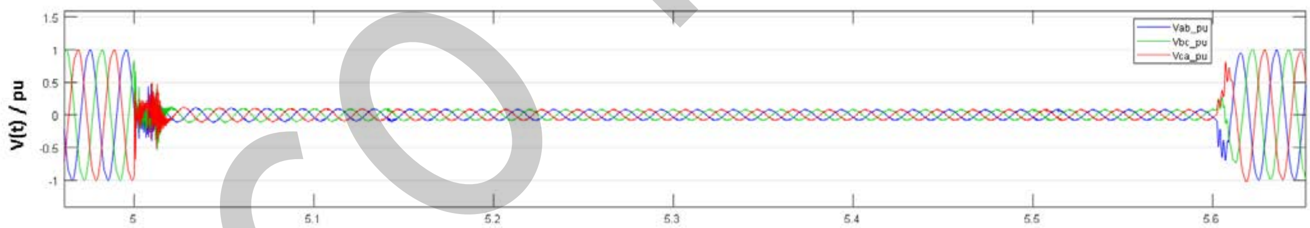


Figure 2.14 Voltage Recovery after grid fault

2.3.2 Consideration of Battery and Power Limits

In general, as well as in grid forming mode, the inverter provides two levels of battery limits to be set. The first level of limits is meant to be followed by derating the power output but can be exceeded for a short period of time, so as not to nuisance trip the inverter. The second level is for an instantaneous fault trip of the inverter.

Since the inverter has the provision of nominal AC voltage and frequency as first goal, the current flowing is decided by the interaction with the loads or other energy sources in parallel. Therefore, the usage of the battery is influenced by the interaction with other loads or energy sources in parallel. Nevertheless, in order to operate within the limitations of the battery, the inverter will adjust its output power according to the droop curves to respect the limitations of the battery.

In Figure 2.15 there is an example shown of a Droop adjustment because of two high active power output. Because the current power output is too high, the inverter will adjust its output frequency (lowering the frequency at too high discharge) in order to achieve a higher power injection from other energy sources.

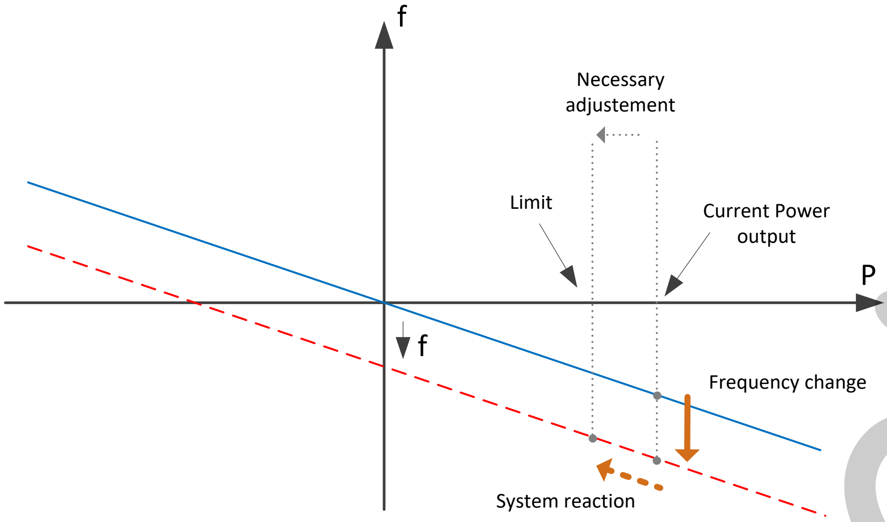


Figure 2.15 Power Adjustment because of Power Limitations

By achieving higher power injection from other energy sources, the power output of the inverter is reduced and the limit can be considered. This principle of output adjustment because of a limitation is applied to three groups of limitations:

- Battery Current Limitations
- Battery Voltage Limitations
- AC Output limitations

Each of these sets of limitations is connected to a PI-Controller which regulates the necessary frequency adjustment in order to operate exactly at the correspondent limitation. Each PI-Controller can be configured individually; the parameters are displayed in chapter 3.

In case of a fully isolated Grid with the inverter as the only power source, the frequency adjustment most likely won't result in any output adjustment since most of the loads have no dependency of the grid frequency. That's why the PI-Controller will increase the frequency change further and further. This frequency change can be limited by the parameter *GriForm.Ctl.HzOutLim* (Default 5 Hz) but also can be used to trip the grid monitoring limits in order to stop the inverter and prevent further exceedance of the corresponding limit.

2.3.3 Overloading Capabilities

The inverter does not have a predesigned overloading capability. If the system requires overloading capabilities for certain function, e.g. 10% for 1 hour, then 10% more capacity will need to be installed. However, the whole project/site requirements shall be considered. SMA can provide an overall system design as requested.

Example: The load is 4 MW; a 10% for 15mins will be needed. Then 4MW * 1.1 = 4,4MW shall be installed. I.e. 2xSCS-2475 will be sufficient for such a requirement (after taking into account other design parameters).

2.3.4 Negative Sequence and Zero Sequence

Asymmetrically-distributed, single-phase loads on the LV side of the load will result in asymmetric load on the medium voltage side. The resulting asymmetry can be expressed in positive sequence, negative sequence, and zero sequence components $\mathbf{I_P}$, $\mathbf{I_N}$, $\mathbf{I_0}$.

The **zero sequence** component $\mathbf{I_0}$ cannot propagate thru the transformers to the inverter as the inverter is only 3Ph without N line. The $\mathbf{I_0}$ will be served thru the load transformer.

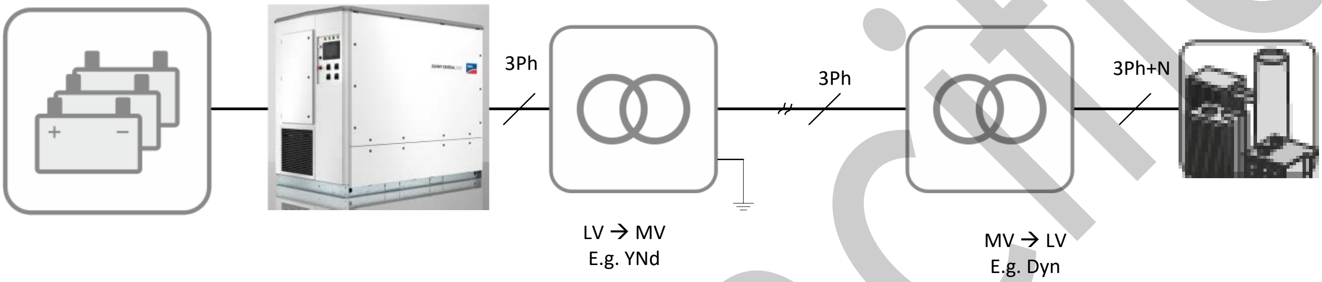


Figure 2.16 Load serving thru two transformers

The negative sequence components can be served by the inverter up to 10% of the nominal current at the LV side. The negative sequence will be transferred to the battery as a 100Hz component or 50 Hz grids or 120 Hz for 60 Hz grids. If higher values are required, then please contact your SMA application engineer for further analysis.

Note: It is always recommended to have sufficient load measurements of the project.

2.3.5 Harmonics in the Loads

Harmonics in the load will be transferred to the inverter and affect the quality of the voltage waveform. The harmonics in the load shall follow the IEEE 1992-519 or lower. The inverter control operates at 3000Hz and its passive filter is designed at cut-off frequency of ~900Hz. If the load contains such level of harmonics, please contact your application engineer at SMA.

Note: It is always recommended to have sufficient load measurements of the site to be served.

2.4 Blackstart

The functionality of starting up a grid from black-out ("Blackstart") has been possible with firmware version 5.01.xx.R and above. Apart from the appropriate firmware version, the functionality of blackstart requires two key elements to be installed: DC-side precharge circuit/assembly and an external power supply for the inverter auxiliary power system.

The DC-side precharge equipment is needed in order to charge the DC link capacitors to the same voltage level of the battery without an energized grid at the AC terminals of the inverter. DC-side precharge equipment can be retrofitted to existing SCS inverters.

An external power supply for the inverters auxiliary power system must be connected to the inverter with the options laid out in section 1.2. In a normal grid-tied system, the inverter derives its auxiliary power from its AC terminals however in a black-out scenario, there is no AC voltage present so for blackstart applications, an external, uninterruptable power supply (UPS) must be connected to the inverter. An example system is shown in Figure 2.18.

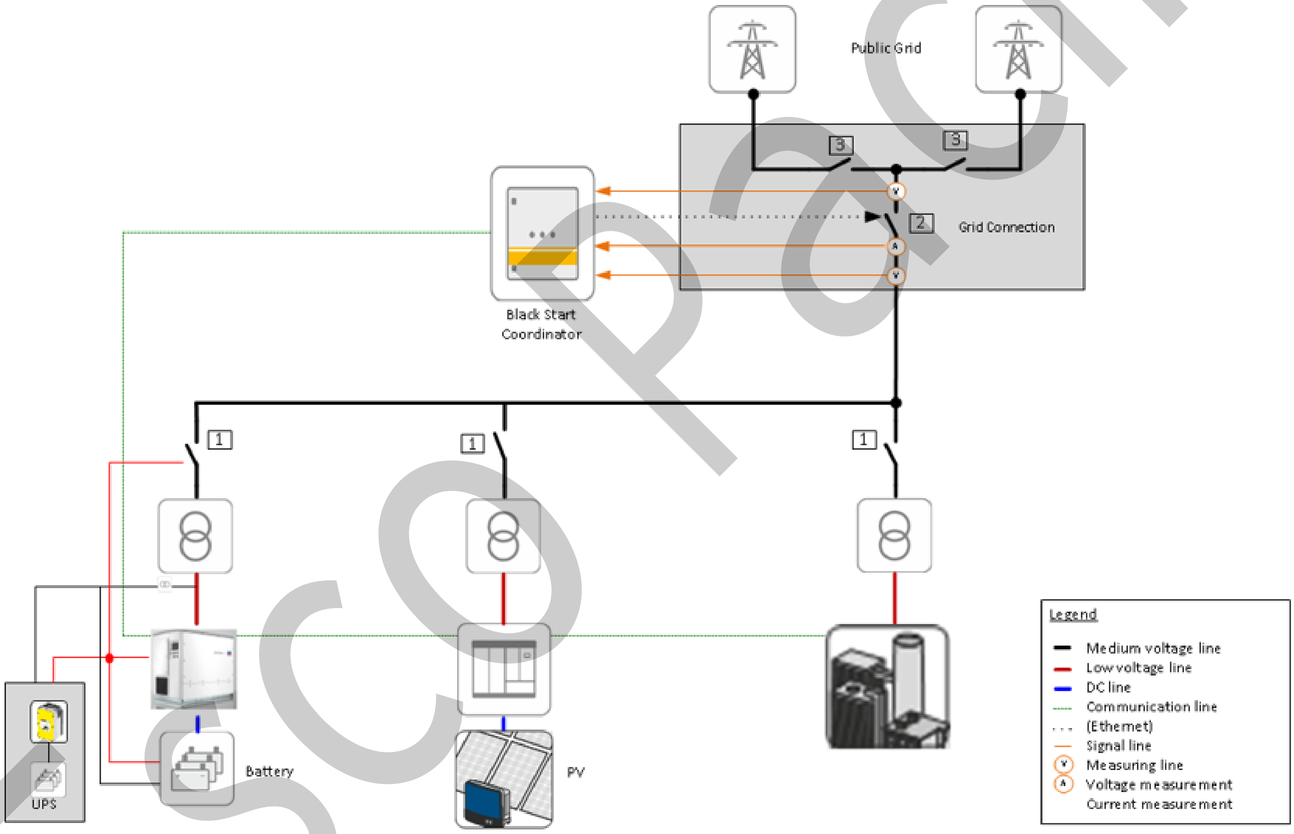


Figure 2.18 Example blackstart system

2.4.1 Startup Procedure

Blackstart is performed by using the same start command as usual (operation command set to grid forming mode). The inverter will detect whether there is an existing grid-voltage to synchronize to or if it has to black-start the grid.

If no grid-voltage is being detected, the inverter will first close its AC-breaker and subsequent ramp up the AC-voltage from 0V to its voltage setpoint within approximately 200ms. This avoids high inrush currents by magnetizing the transformers in the grid.

In case the load of the grid is too high to be supplied by only one SCS inverter, multiple devices can be used for a coordinated blackstart procedure. For this purpose, a first device should be started with a voltage setpoint of at least 20% of nominal voltage, as show in Figure 2.19. The remaining devices must be started and synchronized by using the same voltage setpoint. By slowly ramping up the voltage setpoints the inverters will start-up the grid in common. During this process the voltage setpoints should always be similar for all devices in parallel to avoid high balancing currents between the inverters.

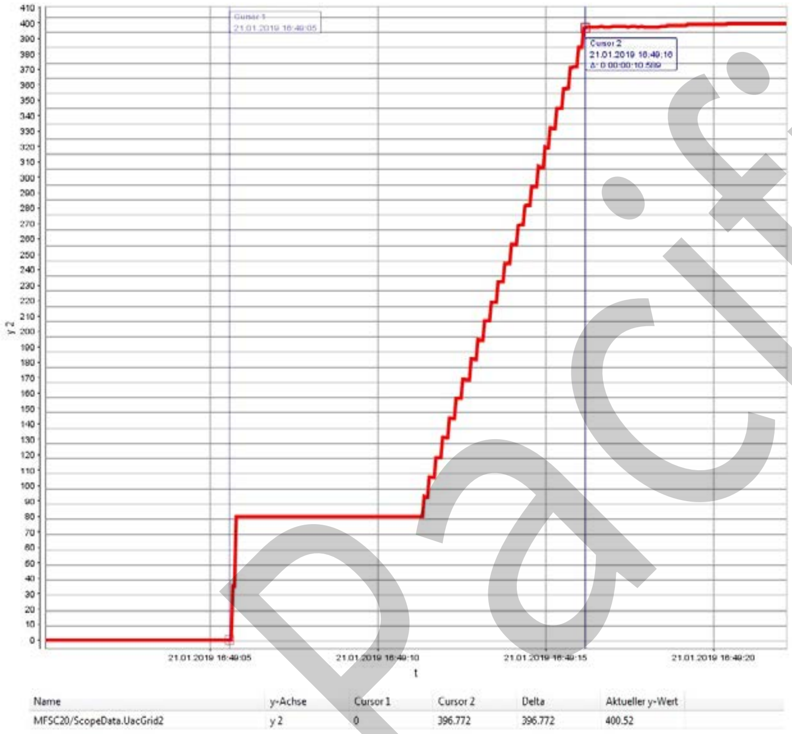


Figure 2.19 Parallel unit voltage ramp-up example

2.4.2 AC-Ramp-Up

During the voltage-ramp-up procedure the inverter stays in the operating-state AC-Ramp-Up (*OpStt = ACRampUp*). In this state the usual grid monitoring limits are still deactivated, so the inverter e.g. will not trip due to low voltage. After reaching the operational voltage and frequency window for the defined time of *GriErrTm*, the inverter will automatically switch to the operating state GridForm (*OpStt = GridForm*) in which the usual grid monitoring limits are activated.

The nominal voltage and frequency are set by parameters *VolRtg* and *HzRtg* with the limits defined by *Vctl.OpmaxNom/Vctl.OpminNom* and *HzCtl.OpmaxNom/HzCtl.OpminNom*

2.4.3 DC Precharge

The DC precharge equipment consists of a contactor, power resistors and fuses. It is designed to allow a fast precharge of the DC-link-capacitors. Depending on the voltage differences, the resistors may become hot during the precharge procedure. In order to allow the resistors to cool down sufficiently the DC precharge can only be conducted once within 10 minutes. If this waiting period has not yet expired, the inverter will remain in "*OpStt = Connect DC*" and show the reason *PwrOffReas* = "WaitDC: DC precharge waiting period".

3 Parameterization of Grid Forming Features

Parameters to be set at commissioning as default values for the Grid-Forming operation. When giving default values, the SCS-2200 will be considered.

Nr	Name	Description	Value-Range and Default
312	HzSpt	Default Frequency to be set	45 to 65 Hz (50 Hz)
310	HzRtg	Nominal Frequency for Grid Monitoring	45 to 65 Hz (50 Hz)
311	VolPsDSpt	AC Voltage Setpoint, Voltage d axis positive sequence setpoint	n.a., (314,35V, refers to 385V)
6095	VolRtg	Nominal AC Voltage for Grid Monitoring	1....1000V (385V)
7576	GriForm.AcCtl.DrpHz	Active power frequency droop	-10 to +10 Hz/pu (-1 Hz/pu)
7577	GriForm.AcCtl.DrpVol	Reactive power voltage droop	0 to 1 (0.050)
7619	RotDirSpt	Direction of the rotating magnetic field	Clockwise, anti-clockwise (clockwise)
3941	Bsc.InvStrMod	Inverter Start Mode, choose DC-Precharge to allow Black-Start	AC- or DC-Precharge

Parameters about Derating in Grid-Forming-State

Nr	Name	Description	Value-Range and Default
7648	GriForm.Ctl.HzOutLim	Frequency setpoint limiting range for the limiting controller	0....20 Hz (5 Hz)
7578	GriForm.DcCtl.AmpKi	Limiting controller, DC Current, Integral amplification	0....1000 (5)
7579	GriForm.DcCtl.AmpKp	Limiting controller, DC Current, Proportional amplification	0....1000 (0)
7588	GriForm.DcCtl.VolKi	Limiting controller, DC Voltage, Integral amplification	0....1000 (30)
7589	GriForm.DcCtl.VolKp	Limiting controller, DC Voltage, Proportional amplification	0....1000 (0)
7652	GriForm.AcCtl.AmpDQLimKi	Limiting controller, AC Current and AC Power, Integral amplification	0....100 (4,5)
7650	GriForm.AcCtl.AmpDQLimKp	Limiting controller, AC Current and AC Power, Proportional amplification	0....100 (0,120)

Parameters about Grid Fault handling

Nr	Name	Description	Value-Range and Default
xxxx	GriForm.Frt.VirtImpLimTm	The maximum duration of the software protection phase (Virtual Impedance mode)	0...1000000 ms (5000 ms)
8011	GriForm.Frt.VirtImpReact	Virtual Impedance mode reactance value	-5...5 pu (-0.3 pu)
8009	GriForm.Frt.VirtImpRis	Virtual Impedance mode resistance value	0...5 pu (0.5 pu)
7627	GriForm.Frt.AMaxNom	Maximum short circuit current during software protection phase	0...2 pu (1.1 pu)

Setpoints to be changed during operation

Can be checked by these Spot-Values

Nr	Name	Description	Unit
7000	VolNomSpt	Setpoint Reflection, AC Voltage relative to VolPsDSpt	Pu
7277	HzNomSpt	Setpoint Reflection, AC Frequency	Hz
320	WSpt	Setpoint-Reflection, Active Power	kW
321	VarSpt	Setpoint-Reflection, Reactive Power	kVar

Can be set by these Modbus-Registers

Unit Id	Register	Name	Data type	Description	Scaling	Example
2	41261/41262	HzNomSpt	U32	Nominal frequency for active power droop	1000	50000 = 50HZ
2	41263	VolNomSpt	U16	Nominal AC Voltage for reactive power droop	10000	10000 = 1 pu
2	40022	VarSpt	S16	Reactive power setpoint	100	5000 = 50% of VArRtg
2	40023	WSpt	S16	Active power setpoint	100	5000 = 50% of WRtg

4 Communication Interface for the Grid Forming Operation

The communication interface in general is unchanged compared to the Grid-Tied Sunny Central Storage and is described in the Technical Information Modbus Interface for SCS / SCS-US / SCS UP / SCS UP-US. Starting from version 1.2. this technical information includes all signals which are needed to control the device in Grid-Forming Operation.

The differences to control the device in Grid-Forming Operation are:

- Operation Command includes Grid Forming Mode
  AuxCtl.SCSOpCmd has the ENUM value 21521 for Grid Forming Mode as new option
- Operating States includes GridForm as new status
  OpStt has the ENUM value 21429 for GridForm as new status
- Offsets for the droop operation can be sent in two ways
  - Active Power and Reactive Power reference as desired output at nominal operation
  - Change of Nominal AC Voltage and Nominal AC Frequency to shift the droop curves

Setpoint signals (same as in standard device)

Unit Id	Register	Name	Data type	Description	Scaling	Example
2	41261/41262	HzNomSpt	U32	Nominal frequency for active power droop	1000	50000 = 50HZ
2	41263	VolNomSpt	U16	Nominal AC Voltage for reactive power droop	10000	10000 = 1 pu
2	40022	VarSpt	S16	Reactive power setpoint	100	5000 = 50% of VArRtg
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