Grid Forming Inverters
Fundamentals and Stability Services Specifications

Frank Berring | Head of Business Development

March, 2024

Agenda

1 Grid Forming Inverter Fundamentals

2 Grid Forming Inverter Specifications

3 Grid Forming Inverters - *a contrast between essential and advanced capabilities*

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SMA Large Scale Energy Solutions – SOLAR, STORAGE, P2G

Grid Following vs. Grid Forming

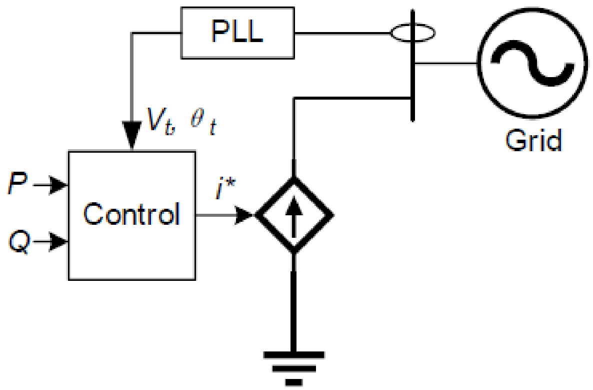
0% 20%…30% **INVERTER PENETRATION** 60%…70% 100%

Grid Following PAST	Grid Supporting PRESENT	Grid Forming FUTURE
Aim: →**Maximum energy yield active power**	**Aim**: →**Grid-friendly active & reactive power contribution**	**Aim**: →**Enable 100% renewable penetration**
Control Tasks: →**Current source** behavior →P priority over Q	**Control Tasks**: →**Current source** behavior →Stabilizing with P&Q →Q over P in some cases	**Control Tasks**: →**Voltage source** behavior →Independent U&f provision (in harmony with other sources)

Grid Following = Current Controlled Source **Grid Forming = Voltage Controlled Source**

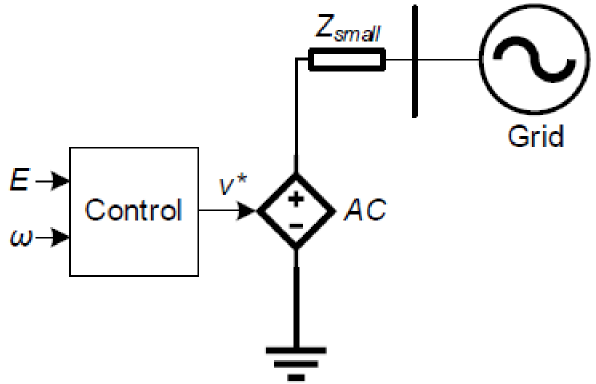
GFL vs. GFM comparison

Grid Following (GFL)



- PLL control is used to generate the output signal of the inverter
- Control the active and reactive power

Grid Forming (GFM)

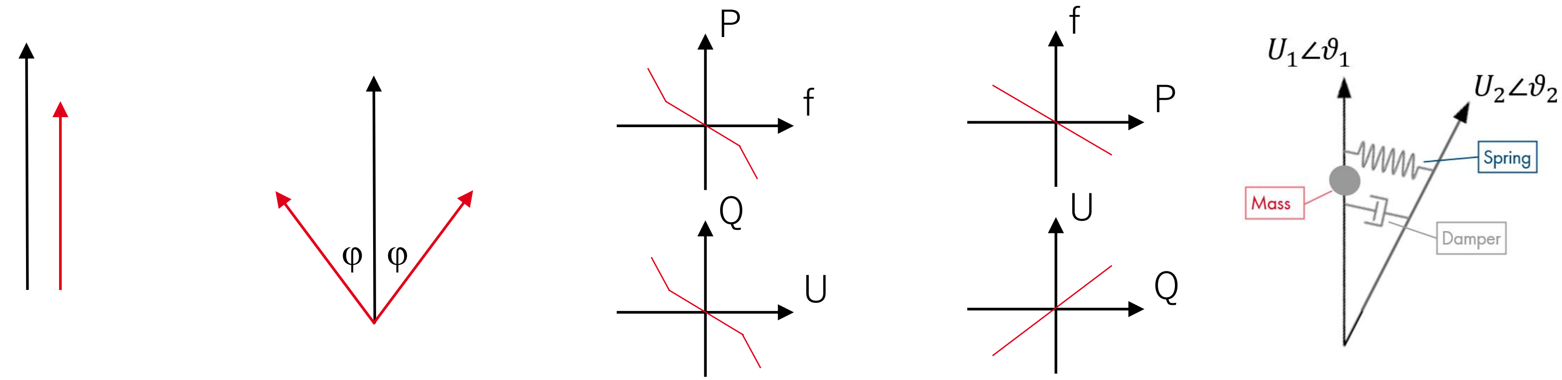


- PLL is only used for measurements in the grid, but no for control
- Control the voltage magnitude and phase/frequency

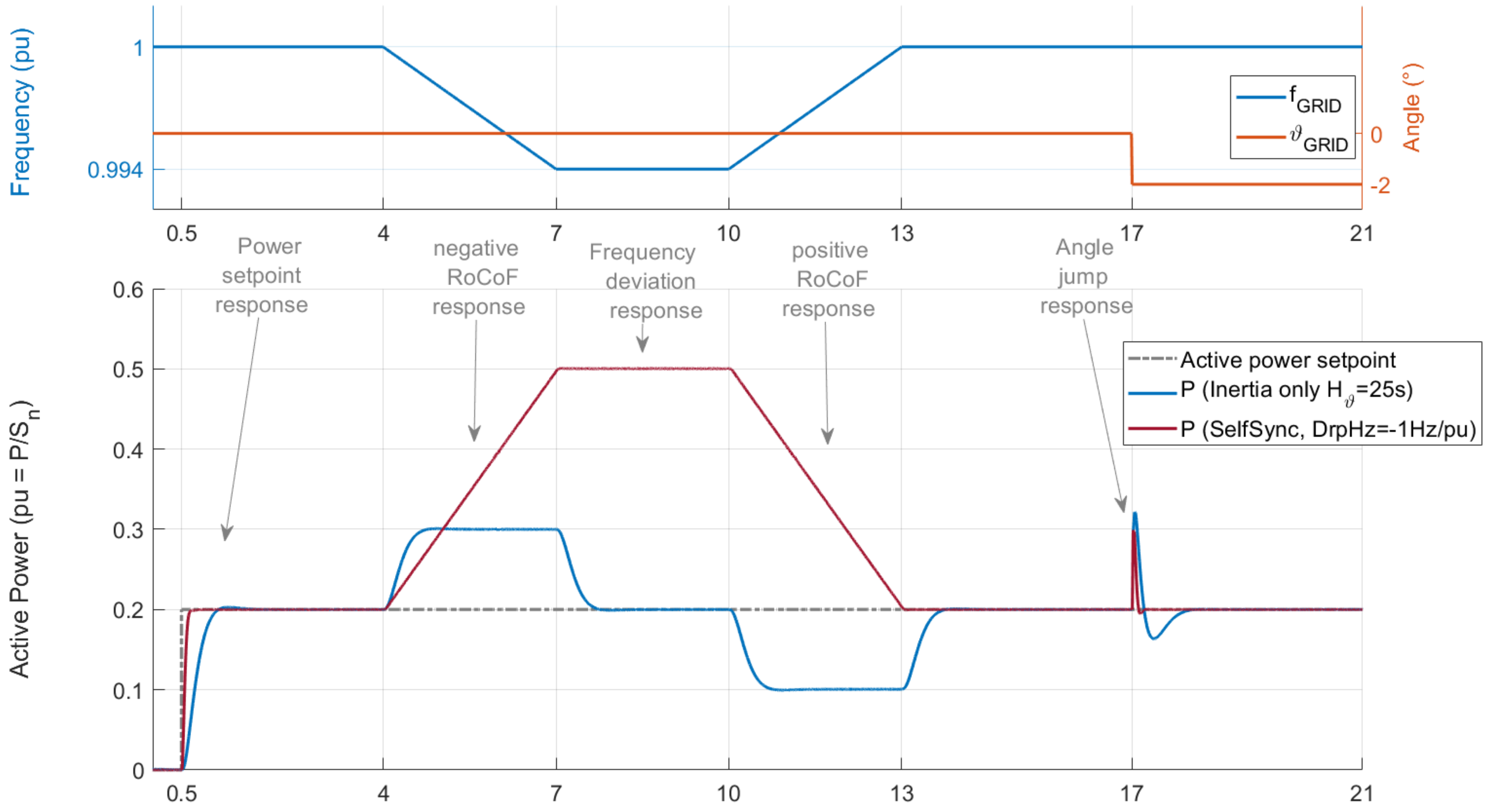
SUNNY CENTRAL STORAGE (SCS) UTILITY POWER (UP) CONVERTERS

High Level Control Modes

- Inverter
  - Grid Following (Current Controlled)
    - P only
    - Cos(φ)
    - P(f) & Q(U)
  - Grid Forming (Voltage Controlled)
    - Droop Based f(P) & U(Q)
    - Inertia Mode*



Summary: Droop vs. Inertia

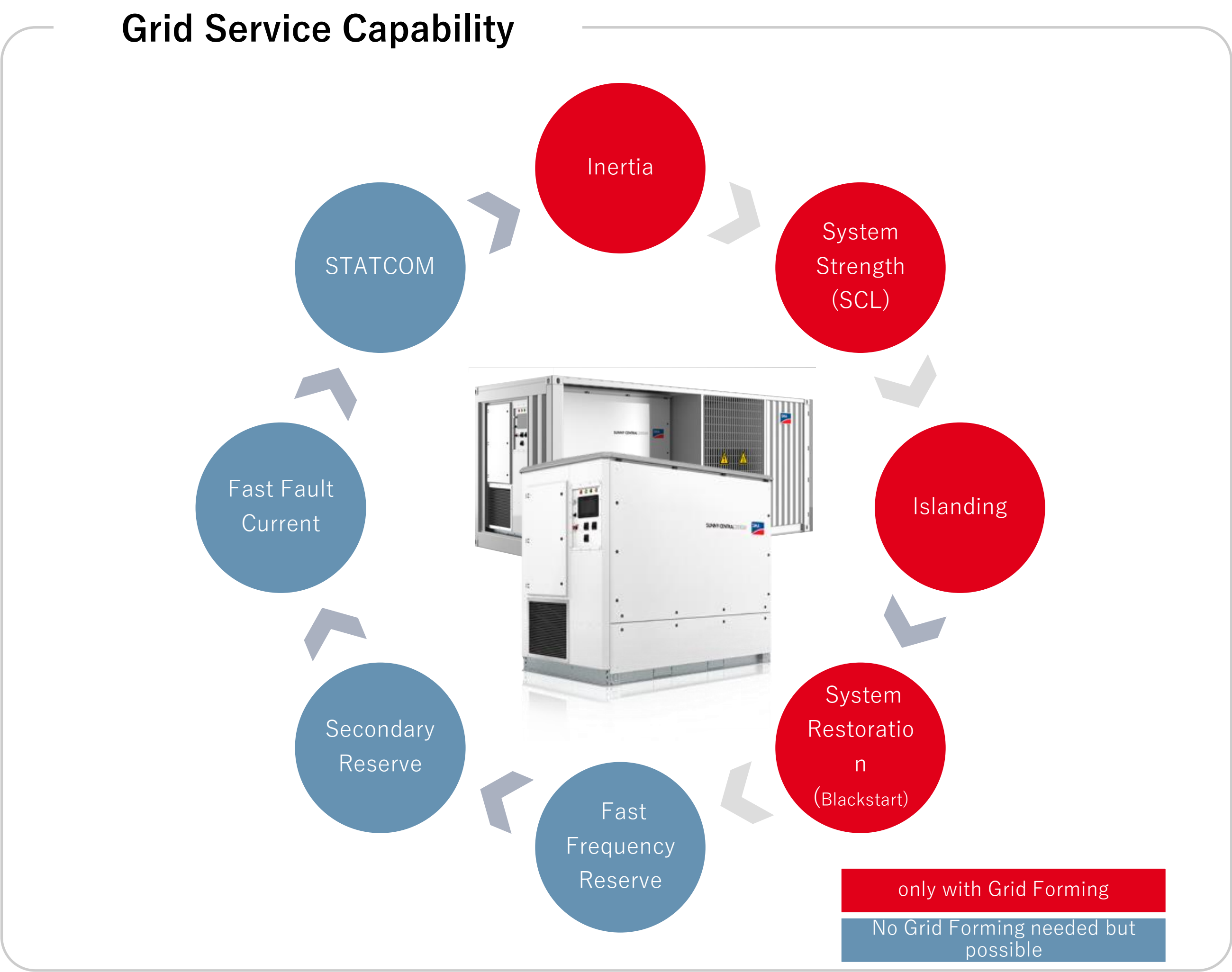


What is Synchronous Grid Forming

- Inverters operating in Voltage Source Control Mode - **Grid Forming**
- In **synchronism** with a large interconnected network
- Stabilizing weak grid regions and the overall power system
- Compatible with existing systems, and enabling 100% inverter-based generation.

Synchronous Grid Forming is the key enabler for 100% renewable generation.

Overview: What Does Grid Forming Unlock?



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Grid Forming – The Essential ISO Specification Should…

Require Voltage Control Mode

- Internal constant voltage phasor
- Operating in synchronism with the network
- Operates stably with LLSM[1]

Require *Capability* of Stability Services

- System Strength Improvement
- RoCoF improvement (inertia)
- Short Circuit Current Provision

1.LLSM = Loss of Last Synchronous Machine …i.e. inverter seamlessly operates as an islanded system when the grid is disconnected

Grid Forming – The Essential ISO Specification Should…

Require Voltage Control Mode

- Internal constant voltage phasor
- Operating synchronism networ
- Operates stably w LLSM[1]

Project specifications for NEW plants, may add "how much" – derived from system impact study

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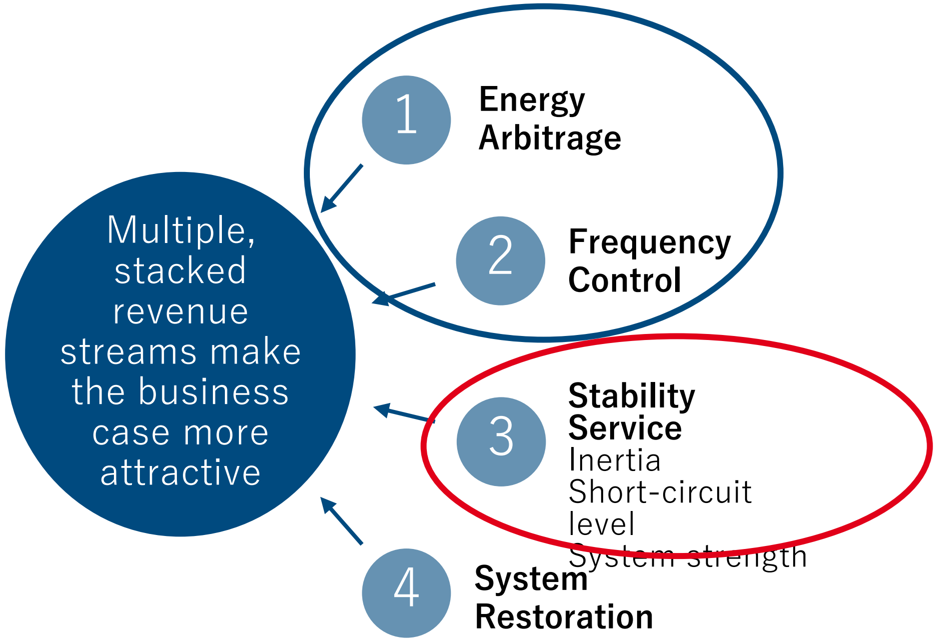
“Basic” vs “Advanced” Grid Forming Asset Designs - *A Closer Look at Stability Services*

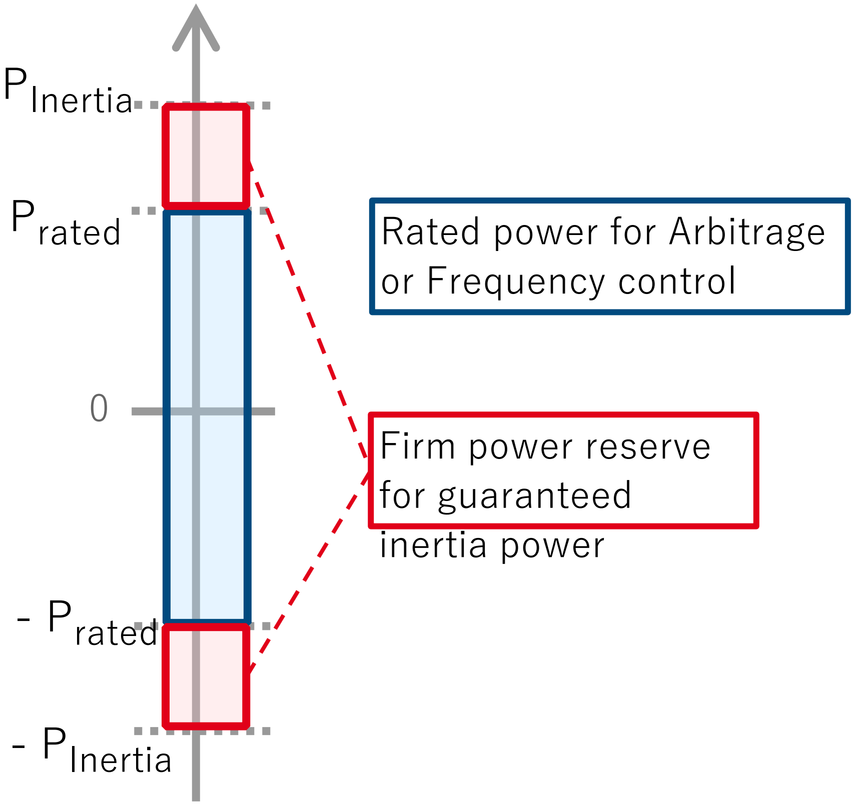
Generator Behavior Benefits of Grid Forming IBRs

- **Instantaneous response to grid events** due to physics of voltage phasor control
- **Ride-through of extreme grid events** overcoming physical limits of electric machines
- **Adjustable power response** for adaption to changing market conditions
- **Reduced risk for asynchronous tripping** with advanced synchronization controls

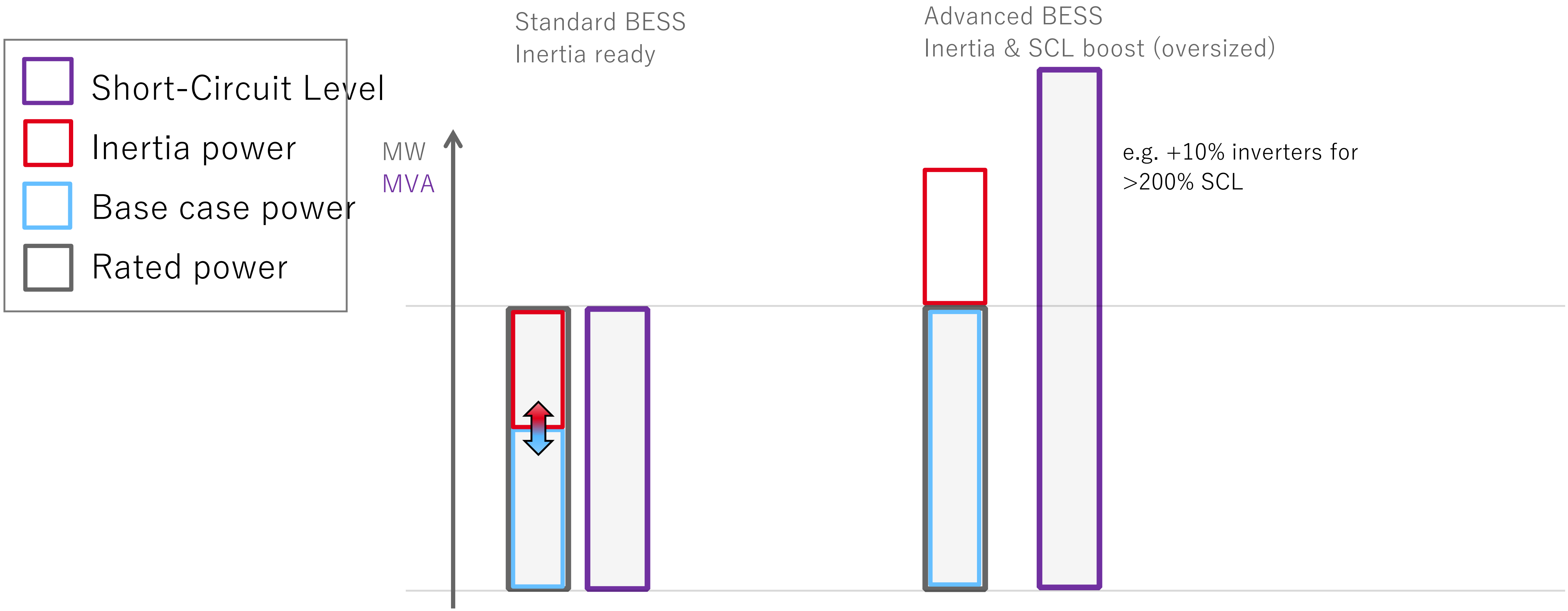
	“Basic” Plant Design w/out Headroom	“Advanced” Plant Designed for Stability Services
System Strength (SCR) Improvement	Improved voltage stability due to fundamental phasor control methodology	
RoCoF / Inertia	Amount of inertia is limited by the state of the plant operation in the moment of need	Predictable, tunable inertia available at all times
Short Circuit Current	Inherent, instantaneous fault current response, but limited to nameplate current	**Current boost** for firm response > 1pu even when plant is operating at nominal power

2023+
Multi-Use of Battery Energy Storage Solution





Designing for Stability Services Inertia and SCL



Flexibility within rated power
Inertia will reduce base case

Inertia on top of rated power
Maximize response and revenues
Requires oversizing **(e.g. +10%)** and boost consideration in initial design

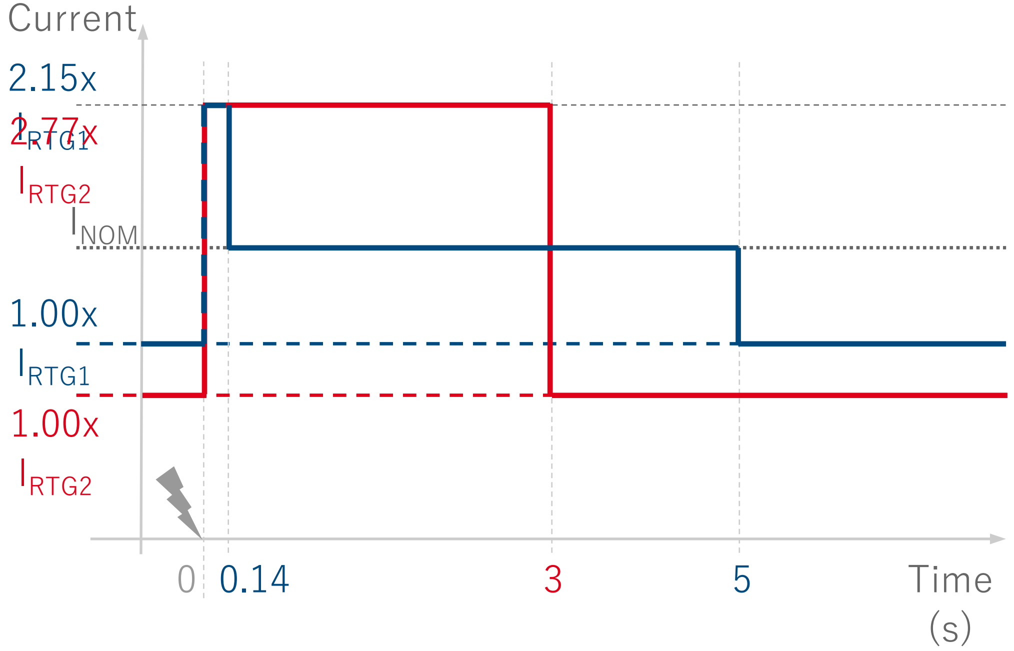
SCS **current boost** profiles for covering typical applications

Profile 1:

- High **short-circuit** current
- Moderate, long-during inertia
- Higher rated power

Profile 2:

- High short-circuit current
- High **inertia** reserves
- Lower rated power



1.Valid for Sunny Central Storage UP and XT inverters (SCS 3450…3950 UP & XT)

CONCLUSION: Grid Services based on different asset classes:
Battery Storage as the multi-purpose tool for future power systems

	Synchronous Condenser	BESS Grid Following	BESS Advanced Grid Forming
PRIMARY/SECONDARY FREQUENCY RESERVE	--	Yes	Yes
STORAGE FOR SYSTEM BALANCING (ARBITRAGE)	--	Yes	Yes
CONGESTION MANAGEMENT (GRID BOOSTER)	--	Yes	Yes
REACTIVE POWER (STATCOM)	Design spec	Design spec	Design spec
INERTIA	Design spec	--	Design spec
FAULT CURRENT / SYSTEM STRENGTH	Design spec	--	Design spec
BLACKSTART / ISLAND CAPABILITY	--	--	Yes

In the US Market, BESS has two distinct Stakeholders

Developer IPPs
***Market-oriented** use cases*

Multiple, stacked revenue streams make the business case

1. **Energy Arbitrage**
2. **Frequency Control**
3. **Stability Services**
   Inertia
   Short-circuit level
   System strength
4. **System Restoration**

System Operators
***Grid Asset** use cases*

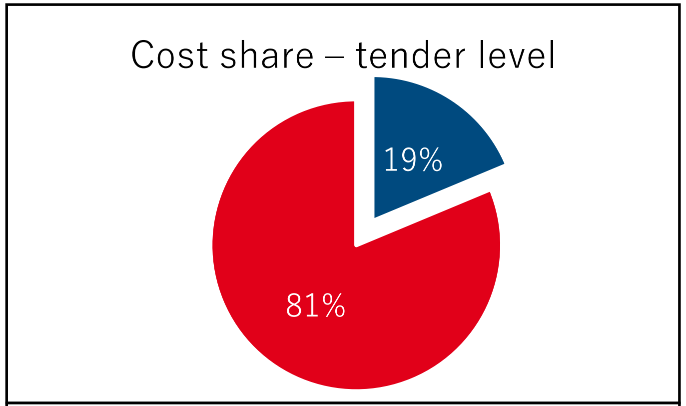
Multi-use Grid Asset

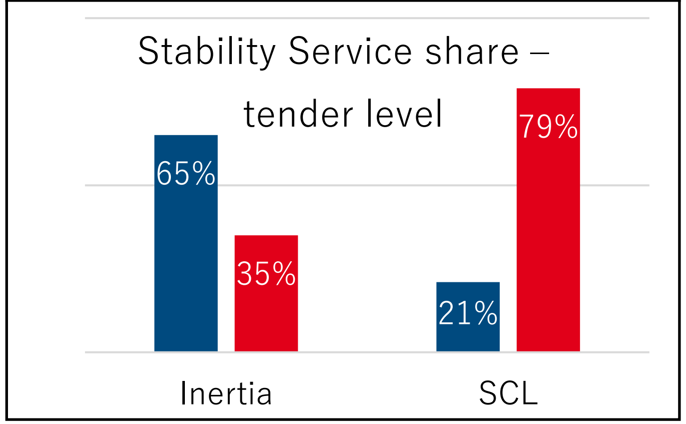
1. **Grid Booster**
   Congestion Management / Virtual Transmission Line
2. **Stability Services**
   Inertia
   Short-circuit level
   System strength
3. **Voltage Control**
   STATCOM
4. **System Restoration**

Stability Pathfinder Phase 2 – Technology agnostic tender Commercial Results and Analysis

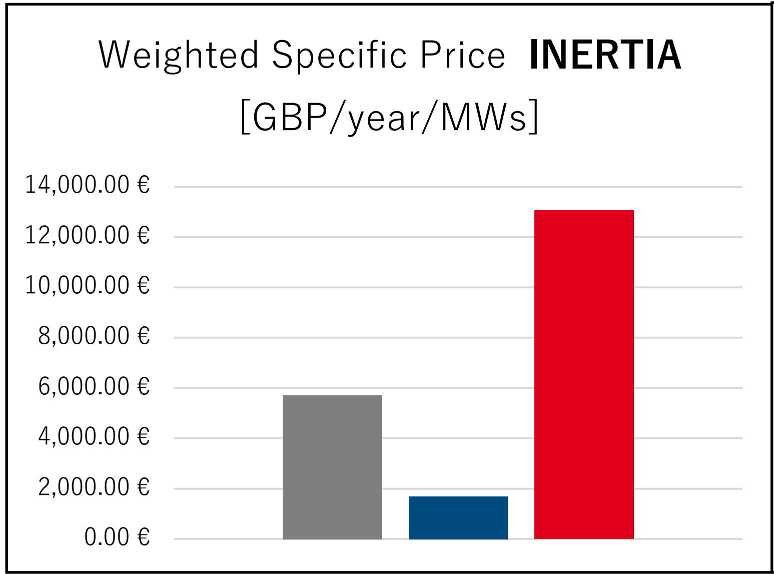
Data Source: NOA Stability Pathfinder | ESO (nationalgrideso.com)

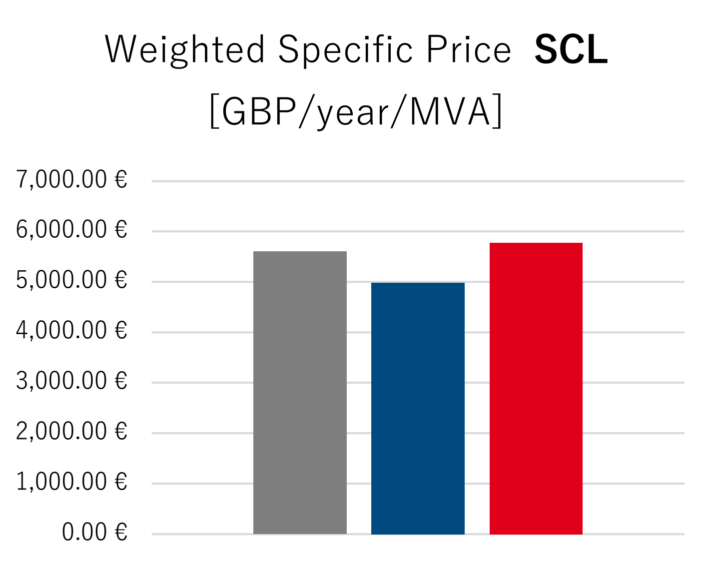
Tende r | BESS | Syncon





Specific cost per stability service (all winners)





	Average Specific Cost Inertia	Average Specific Cost SCL	Sum £/SP for first contract year
Tender level	5.716,82 €	5.604,47 €	£ 2.204,90
BESS level	1.682,28 €	4.979,97 €	£ 418,67
Synchon Level	13.055,80 €	5.774,19 €	£ 1.786,23

Out of 225 projects 5 with Syncons and 5 with BESS have been selected!
BESS is the most competitive solution!

THANK YOU

SMA America, LLC