AEMO Inertia Requirements - SMA Australia Proposal

Project Name	Amendment to inertia requirements
Project Number	N/A
SMA AU Document Number	24-LS-EXT-PRP-01
SMA AG Document Number	N/A
Customer	AEMO
Customer Document Number	N/A

Revision History

Date	Revision	Revision Description	Prepared	Checked	Approved
30/07/2022	A	Issued for Internal Review	ACA		-
02/08/2022	0	Issued for Use	ACA	DGL/APG	ACA

Document Holds

Number	Reason for Hold	Section(s)
HOLD1		
HOLD2		

Table of Contents

APPENDIX A Technical documents

Abbreviations & Definitions

Term	Definition
AEMO	Australian Energy Market Operator
AG	Aktiengesellschaft (translation: public limited company)
AU	Australia
BESS	Battery Energy Storage System
EMT	Electro Magnetic Transient
GFM	Grid Forming
FCAS	Frequency Control Ancillary Services
FFR	Fast Frequency Response
FNN	Forum Netztechnik/Netzbetrieb
HIL	Hardware In the Loop
Hz	Hertz (unit of frequency)
IBR	Inverter Based Resources
ms	Millisecond
MW	Mega Watt (unit of power)
MWs	Mega Watt second (unit of inertia)
NSP	Network Service Provider
POI	Point Of Interconnection
PV	Photovoltaic
PQ	Power and reactive power
RoCoF	Rate of Change of Frequency
s	second
UK	United Kingdom
VDE	Verband der Elektrotechnik Elektronik Informationstechnik
VFFCAS	Very Fast FCAS

References

SMA References

Document Ref	Document Title	Document Number
A1.	SIW21-068_paper_SMA_Knobloch_Andreas	SIW21-068_PAP

Customer References

Document Ref	Document Title	Document Number
B1.	Amendments to the Inertia Requirements Methodology	NA
B2.		

3rd Party References

Document Ref	Document Title	Document Number
C1.		
C2.		

1.0 Introduction

1.1 Purpose

This document provides commentary to the consultation paper titled "Amendments to the Inertia Requirements Methodology" published by AEMO on 5 July 2024.

1.2 SMA

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SMA is a system solution provider focusing on the development and supply of state-of-the-art power conversion, control technology, and engineering services for PV, BESS, and power to gas systems. We have over 40 years of experience at the forefront of enabling technologies for the transition towards decarbonised, renewable energy dominated power systems around the world.

SMA's grid forming technology was developed over 20 years ago and it has since undergone a continuous improvement process to ensure stable, reliable, and affordable inverter dominated power supply systems.

1.3 SMA's general position

SMA supports the inclusion of battery energy storage assets with Grid Forming capabilities into the inertia service framework. These assets are playing a pivotal role in the energy transition and can be designed and used in all major energy, ancillary and stability markets. Our Grid Forming Technology for large-scale assets connected to the grid has been implemented to emulate the behaviour of synchronous machines with an algorithm that enables inherent delay-free response to changing network conditions.

SMA supports the implementation of rules and guidelines in a sustainable and technology agnostic approach to ensure selection and deployment of the best technology while ensuring a swift and sustainable path to a net zero power supply in a socio-economically fair and effective way.

SMA considers inverters with true voltage source controls to behave in an equivalent manner to synchronous equipment, we therefore would recommend against the use of the term non-synchronous to refer to our equipment. True voltage source control is defined in this context as an inverter that remains in voltage source control even in the event of a fault, never reverting to current control during operation.

2.0 General Remarks – Comments on "Explanatory statement and consultation notice"

Section 3.4 – "Methodology improvement: redispatch assumptions":

Considering the unpredictability of network contingencies, we agree on the proposed amendment regarding the impracticality of using dispatch to reduce a generating unit's output in advance. Moreover, that might have a significant impact on the network due to loss of generation.

3.0 Comments on Chapter 2 “Background”

3.1 Comments on “2.1 context for this consultation”

“The Amending Rule broadens the scope of services capable of meeting requirements to qualify as an inertia network service to include synthetic and other non-synchronous service providers. Procurement from these providers is subject to AEMO approval.”

We understand the market design is largely based on specific competitive tender issued by the relevant NSP triggered by identification of shortfall as per AEMO's report. SMA proposes an inertia market based on $/MWs paid according to plant desired availability, for example, >95% under a fixed time-based contract (e.g. 10 years).

SMA considers the ability of the equipment to remain in voltage control mode at all times, including during a system fault, to be a critical characteristic of any asset dedicated to providing system strength, including inertia.

4.0 Comments on chapter "3 Proposal discussion"

4.1 Comments on "3.1 NER requirement: system-wide inertia level and inertia sub-network allocation"

Question 1: *"Do you consider the proposed high-level methodology for determining the system-wide inertia levels and inertia sub-network allocations is appropriate?"*

SMA considers the proposed methodology sound, we would like to express some concern regarding overlapping between frequency markets, in particular VFFCAS and inertia market, we are of the opinion that these markets are different and complementary to one another, frequency response does not substitute the provision of inertia.

Question 2: *"If not, what specific alternatives or additions might better address the NER requirement, and why?"*

SMA would like to see a clearer differentiation between frequency markets and the inertia market as a mechanism to prevent "cannibalization" between these. Inertia is an inherent, delay-free response, whereas VFFCAS is a response to a measurement, and it operates in a longer time scale.

Question 3: *"Are there any other issues relevant to the system-wide inertia level and inertia sub-network allocation methodology that AEMO ought to take into account?"*

The proposal is largely focused on inertial response to RoCoF. Has inertial response based on voltage angle deviations been considered?

4.2 Comments on "3.2 NER requirement: process for determining sub-network islanding risk"

Question 1: *"Do you consider the proposed factors for classifying sub-network islanding risk are appropriate?"*

SMA considers the sub-network classification factors appropriate for the purpose of this consultation.

4.3 Comments on "3.3 NER requirement: inertia network services specification"

4.3.1 Comments on "3.3.1 Issue description"

SMA supports certification of equipment. Plant level performance should be validated via laboratory and HIL testing of equipment and plant level simulations with EMT capable software for provision of inertia and other stability services by AEMO. We would like to express our interest in working with AEMO collaboratively to explore how advanced inverter technology can best support the network and exchange experience and knowledge to ensure a successful deployment of an inertia market.

4.3.2 Comments on "3.3.2 Proposal for synchronous inertial response"

SMA understands that assessment of performance should be done at plant-level as well as equipment level as the critical point where stability must be maintained and measured is at the POI. Additionally, we would request a more detailed explanation of the rationale behind the exclusion of alternator-based technologies from such an approval procedure.

4.3.3 Comments on "3.3.3 Proposal for synthetic inertia performance parameters and requirements"

Quote: *"The service must provide a synthetic inertial response in the form of a fast change in active power during system transients such as load or generation trip or a system split which results in a frequency change."*

Suggestion to amend wording on: "[...] *in the form of an inherent change in active* [...] *which results in a voltage angle or frequency change*." We suggest using wording in line with what is becoming industry standard terminology in other markets around the world such as "Active Phase Jump Power" or "RoCoF Power".

Quote: *"Initiation of the synthetic inertial response must be inherent; that is, it should not require the calculation of frequency or RoCoF through measurements of the grid voltage waveform."*

We agree that inverters equipped with advanced functionality for the provision of grid services do not need to detect a frequency disturbance, they must react inherently to frequency events or voltage angle changes. This reaction is immediate and therefore there is no time delay. We suggest defining inherent response as a current/power response that occurs within <5ms of the disturbance.

Quote: *"The service's resistance to change in frequency is bi-directional; that is, it must act to resist frequency change for both rising and falling frequency events."*

We agree that a symmetric response is necessary as asymmetric inertial responses may cause frequency drift and oscillation issues in the power system, thus negatively impacting stability.

Quote: *"The inertia constant of the service must be tuned based on both local and broader network conditions and requirements if configurable."*

We would request some clarification on this statement to help us answer the following questions:

1. Is the ability to configure inertial behaviour considered necessary?
2. Will configurability of inertia be mandatory?
3. What would be the desired range of tuneable inertia constant?
4. What conditions would trigger different inertia constant values?
5. Would a proposed system have to perform modelling for a range of different inertia constant values?

Quote: *The service must have sufficient energy buffer to provide an appropriate active power response during system transients without being limited.*

The size of the energy buffer needed is dependent on the specific inertia constant setting as well as expected RoCoF value. There are several different ways to provide an energy buffer, when it comes to IBR we see the main methods for provision of an energy buffer are (1) using boost capacity (sometimes referred to as overload) of the inverters, (2) rating the system below its nameplate rating so that some capacity is reserved for contingency response, or (3) combination of the two methods. Inverters have limited boost capacity so relying on that alone would require a significantly higher number of assets to provide the same service, on the other hand, reserving capacity has a cost to the project in the form of lost potential revenue which must be compensated to make it attractive. A firm inertia provision in MW is necessary, otherwise the inertia service loses effectiveness. Therefore, an availability threshold should be defined, e.g. 95% fixed contractually.

4.4 Questions on "3.3 NER requirement: inertia network services specification"

Question 1: *"Are the proposed parameters and requirements for a service to qualify as an inertia network service appropriate?"*

The parameters and requirements are generally appropriate but further detail and additional criteria would be required to fully understand the inertia market design (e.g. what is the unit of inertia that will be procured? MWs, MW, etc.)

Question 2: *"If not, what specific additions or alternatives should be included, and why?"*

The conditions under which the inertia service should be provided as well as expected performance needs to be outlined to ensure proponents can optimise designs to deliver the expected or desired outcome (e.g.

Figure 1 - Reference frequency curve for validation of inertia power and energy response

is provided as an example of a RoCoF Profile extracted from VDE FNN Requirements)

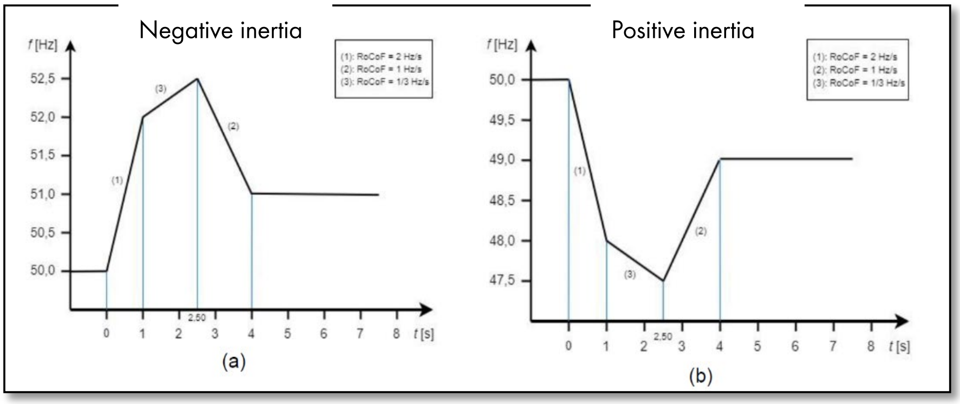

Figure 1 - Reference frequency curve for validation of inertia power and energy response

We propose the implementation of a RoCoF test to determine compliance. The following extract from the specification of UK Stability Pathfinder is used as an example:

- For a Design-RoCoF (for example 1 Hz/s or for a specified first frequency profile) in a specified frequency range (for example for a worst-case event between 52 Hz and 47 Hz with up to 5s duration) the power plant should not hit any capability limits for firm inertia provision.
- For a maximum expected RoCoF (for example 2 Hz/s or for a specified second frequency profile) the power plant should ride through the event while hitting the capability limits.
- The RoCoF-Test should be performed from different operation points.

Question 3: *"Which of the approaches outlined for estimating the inertia level provided by a non-synchronous equipment do you consider most appropriate, and why?"*

SMA considers 1(a) the most appropriate methodology for estimating inertia level provided by IBR, especially since it demonstrates grid forming capability of the equipment. 1(b) and 2 may also be passed successfully by using grid following controls and may not be appropriate to determine the actual capability of the equipment for the provision of grid support during critical network events. While any of the proposed tests may be able to evaluate the inertial behaviour of the equipment, to ensure that a voltage source control is used, we recommend including a test that validates the contribution of "active phase jump power" in case of a sudden voltage angle change at the POI.

Question 4: *"Are there any alternative approaches to estimating the inertia level provided by non-synchronous equipment which AEMO should consider?"*

SMA proposes the introduction of a RoCoF test for performance testing, the extract from UK Stability Pathfinder above could be used as a suitable example. A set of RoCoF events may be applied at the plant in simulation using a validated model to evaluate if the desired inertia can be provided during a network frequency event.

Question 4: *"Are there other issues relevant to the inertia service specification that AEMO should consider?"*

We recommend considering impact of damping and inertia constant as these parameters influence the dynamic of power provision during a given RoCoF profile as shown in Figure 2 provided as an example below.

Figure 2 shows the respective active power response profile to the frequency curve in the second graph (blue). The bottom graph shows two different energy output responses. The energy flow between the light blue and yellow response is different even though the inertia constant is the same in both cases.

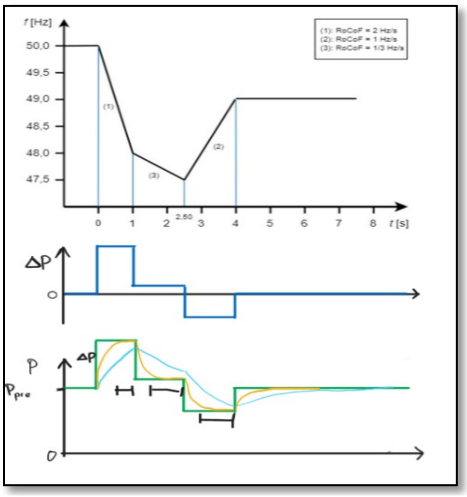

Figure 2 - Impact of damping and inertia constant during RoCoF

Comments on "3.4 Methodology improvement: redispatch assumptions"

SMA considers that frequency markets such as FCAS, FFR, and VFFCAS should not replace but exist in parallel with an inertia market as these are not a substitute but rather a complement to each other. Some thought should be given to preventing the possibility of different markets overlapping one another.

4.5 Comments on "3.5 Methodology improvement: credible events leading to island formation"

SMA agrees with the approach of considering the high-risk critical situations like interconnector flow down to zero and islanded sections of the network. Therefore, consideration on sub-network inertia requirements is of critical importance.

We consider the proposed amendments for the calculation of inertia in each inertia sub-network appropriate.

4.6 Comments on "3.6 Methodology improvement: additional modelling considerations"

Other markets around the world are implementing standardised network models for relevant sub-networks to aid proponents with assessing project viability by facilitating initial feasibility studies without the need to commit to full connection studies at an early stage. Implementation of cloud-based network models may be an interesting initiative for the Australian market to support project proponents in the initial stages of project assessment.

5.0 SMA Grid Forming Solution

5.1 Overview on Grid Forming Applications

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

1. Microgrids / Island grids
2. System Stability as Grid Service
3. Enable Grid Connection in Weak Grid Areas
4. Blackstart / System restoration

For the purpose of this document, we will focus on points 2 and 3, particularly on the inertia functionality and its implementation on the NEM.

5.2 Design considerations and their impact on stability and economics

Inverter technology offers great flexibility for system tuning, this is especially true when it comes to voltage-controlled inverters. By utilising this flexibility systems can be designed to provide grid services and contribution to network stability in line with relevant incentives in the market.

This section discusses how the market incentives can have a significant influence on the IBR systems' ability to provide grid services in addition to the more common revenue sources already in use such as energy arbitrage and participation in ancillary markets.

Figure 3 shows three examples of systems optimised to deliver different services.

1. Plant A represents a conventional design for IBR plants making use of the standard equipment output rating and therefore having to compromise between capacity to provide inertia and SCL contribution and capacity for arbitrage and ancillary services.
2. Plant B uses the same number of inverters as plant A, the main difference is that the SMA boost function is activated, this function allows for a large increase in maximum output by reserving some of the thermal capacity by a reduction of ~10% of the continuous rating of the inverters. This results in greater capacity of up to 1.6pu for inertia and 2.4pu for SCL contribution.
3. Plant C is designed to optimise the system's capacity to deliver grid services, it uses around 10% more inverters than plants A and B, this oversize together with the SMA current boost function allows the system maximise participation in all relevant revenue streams. For a marginal increase in capital expenditure in the form of additional inverters, the potential to generate revenue from provision of inertia and SCL contribution as well as the ability to participate in energy arbitrage and ancillary service markets can provide a very significant increase in revenue potential. We consider this type of design most appropriate to deliver network stability contribution.

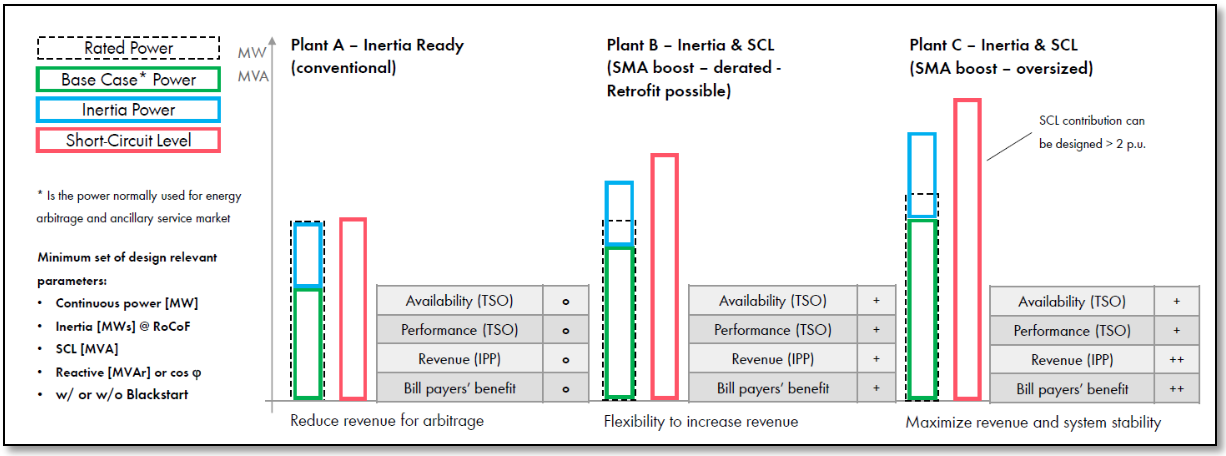

Figure 3 - Approaches to system design optimised for different outcomes

5.2.1 PQ capability of SMA Grid Forming Solution with current boost

This section is used as an example of how a requirement or assessment around IBR system's capacity for providing grid services such as inertia and SCL contribution as well as energy arbitrage and ancillary services could be defined. We understand this graphic representation provides a clearer picture of what is shown in Figure 3 for a specific system.

Figure 4 shows the PQ capability curve of an exemplary BESS designed to provide rated active and reactive power (PQ) within the limits marked by the grey area, short-circuit level shown in red and short-term PQ represented by the blue area, and energy for firm inertia provision for a specified maximum RoCoF (green and light blue arrows) within the system's capacity limits.

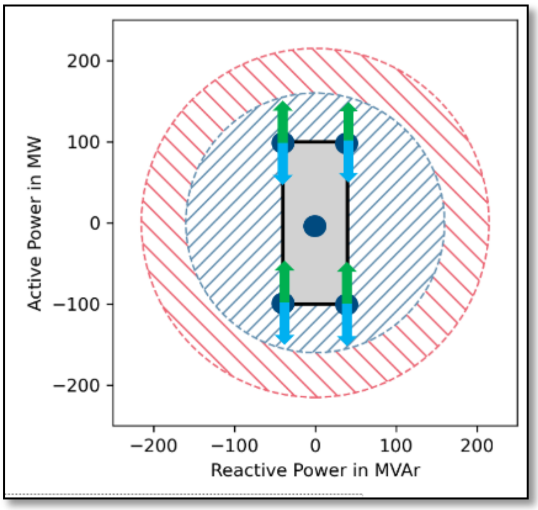

Figure 4 – Generating unit's PQ Capability representation

6.0 SMA Inertia and current boost solution

This section provides a brief overview on how the inertia function from SMA works and the benefits that current boost functionality can provide when it comes to providing system strength services.

[redacted]

[redacted]

6.2 SMA Current Boost

The ability of generating systems to provide high peaks of current can be beneficial for the power network as it is the main parameter contributing to the network's ability to isolate and clear faults. It also provides resilience and ability to maintain voltage and frequency within desired tolerance ranges.

IBR are limited in the current they can output by the maximum current rating of the switching electronics. This means that overload capabilities are limited and very much dependent on system design rather than inverter capability, overload capacity can be defined in this context as the difference between the nameplate rating of the system and the maximum rating of the switching electronics.

Current boost from SMA is a function by which the inverters can access increased current rating of the IGBTs in the order of 2.5pu or higher for a short period of time. Figure 6 shows an example of two different system designs that provide different overload capabilities. The desired load profile can and must be determined according to specific requirements or desired functionality.

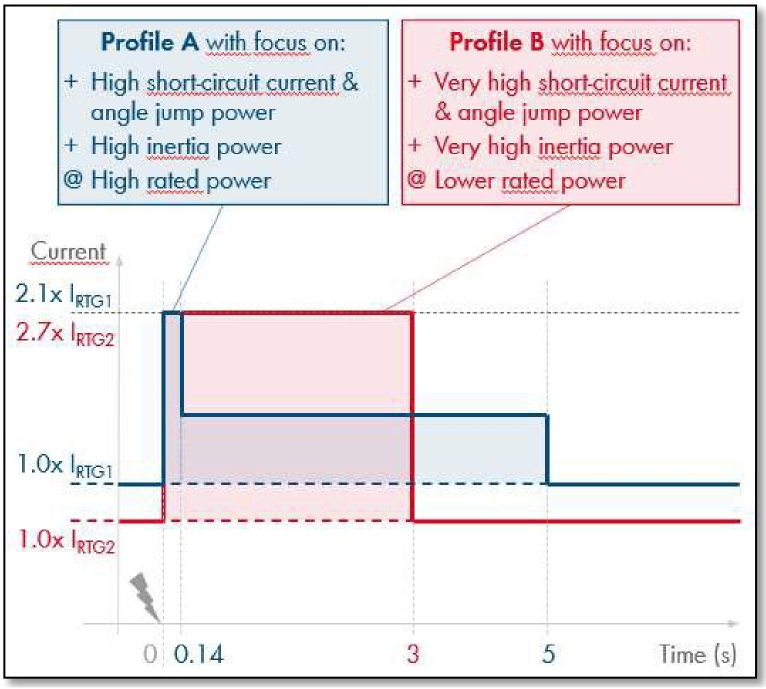

Figure 6 - Example overload profiles given by different system designs

SMA Current Boost unlocks additional current output capacity that can be utilised for the provision of inertia and/or short-circuit level when needed to fulfil specific system requirements. An example of how SMA's current boost function can be used to fulfil requirements for inertia, energy arbitrage, and frequency control is provided in Figure 7.

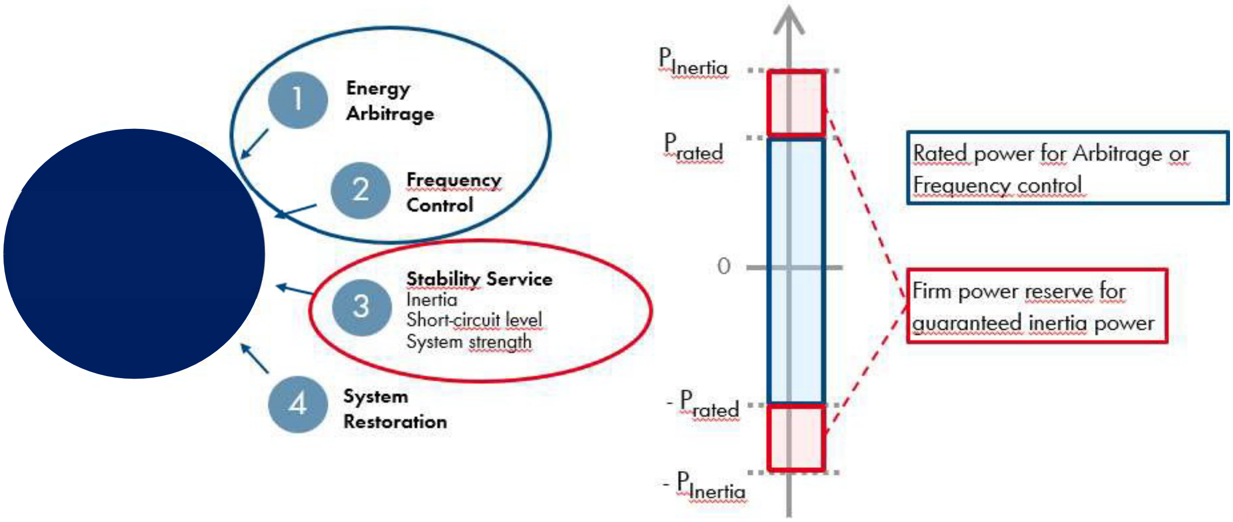

Figure 7 - Use case example for current boost

6.3 Multi-use of IBR with Battery Energy Storage System

As discussed in previous sections of this document, SMA's GFM and advanced inverter functionality provides several essential grid services and the flexibility to enable or disable as well as configuring them independently to achieve the desired system functionality.

Figure 8 provides an overview of some of the main functions available within SMA inverters.

Figure 8 - Grid support services from SMA inverters

The ability to access a wide array of functions and grid services is often referred to by SMA as "Service Stacking". Figure 9 provides an example of Service Stacking by showing how several grid services operate together within the same system to maximise the value the IBR system delivers to the network. This example shows a BESS project capable of providing active power for energy shifting (grey dotted line), and how the resulting power response behaves when stacking Dynamic Containment (yellow line), or Inertia (blue line), or both Dynamic Containment and Inertia (purple line) for illustration purposes.

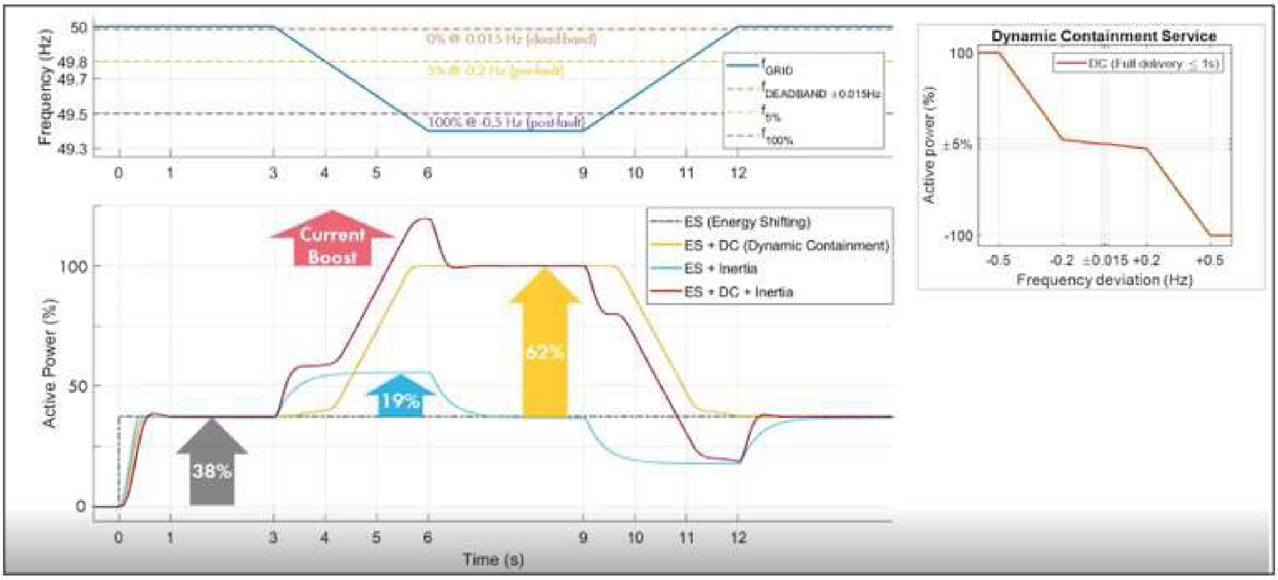

Figure 9 - Example of service stacking functionality

Appendices

APPENDIX A Technical documents

APPENDIX A Technical documents

Item	Document Title	Document Number
1.	SIW21-068_paper_SMA_Knobloch_Andreas	SIW21-068_PAP

Synchronous Energy Storage System with Inertia Capabilities for Angle, Voltage and Frequency Stabilization in Power Grids

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Abstract— **In future power systems voltage and frequency will mainly be formed by synchronous inverter-based power plants with advantageous capabilities compared to today's synchronous machines. This paper introduces a synchronous energy storage system solution (SESS) with grid forming capabilities for voltage, angle and frequency strength improvement in distribution and transmission networks. Configurable control modes for inertia and damping provision are presented. Application examples and performance capabilities for inertia, instantaneous fault current, power oscillation response as well as power reserve provision are shown based on simulation results and practical laboratory experiments. The challenges for accelerated grid integration of SESS are outlined as well.**

Keywords—Grid forming, energy storage system, inertia, voltage, angle, frequency control

I. INTRODUCTION

Power system stability is an essential precondition for the success of the energy transition towards decarbonization and reduction of the dependence on fossil fuels. Loads, but also conventional and renewable generators, rely on stable voltage, angle, and frequency conditions at their point of connection (PoC). Otherwise, they are often not able to perform properly or must completely disconnect from the power grid for protection. To ensure stable conditions and to prevent blackout situations at any point in the electricity network, system voltage, angle, and frequency, but also their rate of change must be controlled and kept within permissible limits and at steady state after transients.

In today's AC power systems voltage, angle and frequency are formed and stabilized mainly by large centralized power plants with synchronous generators and their grid stabilizing mechanisms. These mechanisms include control capabilities like voltage and frequency forming control, black start as well as a flexible but defined active and reactive power provision. But they also include the inherent physical properties of the power plants energy conversion components, like the inertial dynamics, the transient fault current and overload capabilities, as well as the energy storage availability. The utilization of these capabilities enables owners of conventional power plants to provide static and transient power reserves for multiple ancillary services beyond the traditional energy business. At the same time, power system operators rely on and make use of these capabilities for power grid stabilization.

However, power systems around the globe encounter a fundamental transformation. Encouraged by regulatory frameworks and economic incentives, endeavors for a more carbon-free electricity generation mainly from renewable sources initiated an unprecedented technological progress. Within recent decades, renewables and especially solar photovoltaics became the cheapest source of power in many countries [1]. Consequently, the number of renewable generators in power grids is continuously growing, while aged and unprofitable fossil-fuel generators retire together with their grid forming mechanisms. Within this structural transition, system operators are facing challenges not only with high and volatile power flows, network congestions and inappropriate protection. Regional shortfalls of inertia, short-circuit level, system strength, power quality and a decreased availability of black start resources increasingly impact the capability of interconnected grids for stabilization especially after major grid events [2,3,4,5,6,7]. To ensure a stable, secure, and resilient system operation, all these measures must be maintained at permissible levels. Therefore, there is a need for enhancement of the grid stabilizing mechanisms especially in network regions with very low or even no synchronous generation running. Various solution approaches are under discussion or realization to preserve power system stability. These include the synchronous machine-based must-run-unit preservation, the physical or virtual power line augmentation and the installation of additional equipment like synchronous condensers or dynamic statcoms [8,9,10]. In addition, new arrangements for the procurement of enhanced stability services are under development [11]. First non-mandatory, minimum requirements specifications for grid forming systems are being set up, providing the opportunity for enhanced inverter-based solutions to participate in emerging markets [12].

Advanced inverter-based energy storage solutions with grid forming capabilities have successfully proven their ability to establish a stable and secure island and micro grid operation [13,14,15,16,17,18]. Results of extensive large-scale power system studies and real-life demonstrations let system operators recognize the eligibility and the enormous potential of these technology for stabilization of large, interconnected power systems [19,20]. The aim of this paper is to introduce a synchronous energy storage system (SESS) that operates in synchronism with the power system, just like synchronous machines do. Compared with its conventional counterparts the inverter-based system offers beneficial grid forming capabilities that can cover multiple needs in a variety of large-scale applications at distribution and transmission system level. Moreover, it is ideally suited to extend new and existing PV systems and other network participants with profitable grid forming features.

The following chapter II gives an overview on the grid forming capabilities of a SESS and provides recommendations for its design. In chapter III the system concept together with the system components and the control modes of the SESS solution are presented. Chapter IV shows application examples with the SESS solution based on laboratory and simulation results. In chapter V challenges and possible solutions regarding grid integration and appropriate plant design are discussed.

II. GRID FORMING SYSTEM DESIGN CONSIDERATIONS

Grid forming systems, like the SESS, take on responsible tasks to either partly contribute to stable power grid conditions or to establish them independently. This chapter gives a rough overview on the capabilities and recommendations for planning and design of grid forming capable SESS.

A. Grid forming service scope

Depending on the application a SESS is intended to be used for, its grid forming capabilities or services can include without limitation:

- voltage source (behind an impedance) behavior for independent voltage provision capability,
- synchronization capability with other voltage sources,
- inertia capability for limiting voltage vector shift,
- instantaneous (disturbance) response to grid events without any delays,
- contribution to damping,
- voltage quality improvement capability,
- uninterruptible power supply capability,
- black start capability,
- synchronous short circuit/fault level contribution,
- system strength enhancement.

B. Current, voltage, power, and energy headroom

The provision of grid forming services, where the focus is on stabilization of AC grid parameters like voltage, angle, and frequency, typically requires compensation and withstanding of instantaneous power response and energy exchange at sudden grid events. Therefore, the availability of adequate transient and static power and energy reserves, current and voltage headroom at power plant level (PoC) are a prerequisite. The temporarily overload capabilities of the SESS components are limited and depend notably on the individual inverter type. At operational limits or when the reserves have been exhausted, the grid forming capabilities cannot be maintained. Hence, the reserves for grid forming functions need to be considered in the power plant design, usually in addition to the operational range that is to be provided by the power plant besides the grid forming response. Therefore, the SESS designer must be aware about the relation between transient and nominal power provision and consider the power flow to the energy storage.

The amount of the required reserves for grid forming operation usually depends on the scope and extent of the grid forming services as well as on the expected load profile and disturbance level at PoC. Heavy compensation profiles due to high local disturbance conditions or a heavyset grid forming service provision can increase the stress and accelerate the aging of the power plant components. Various control functions and adjustment options of the comprehensive SESS controls usually have a significant impact on the static and transient compensating power and energy exchange with the power system. For effective capability evaluation and target-oriented component design, based on the load profiles to be expected, detailed EMT (Electro Magnetic Transient) simulation studies and optional engineering service support are recommended. Therefore, the project specific requirements, circumstances and objectives need to be specified. The specification should ideally include worst-case scenarios for the intended grid forming service provision and consider potential future service needs.

III. SYNCHRONOUS ENERGY STORAGE SYSTEM

The design of grid forming solutions for various large-scale applications requires an overall system approach with a careful selection of all power plant components, that must match with the control capabilities and objectives as well as with the conditions at the given PoC or at a chosen point of stability (PoS). Solutions that enable a simplified, but flexible design are highly desirable. Therefore, SMA developed a standardized, scalable system solution with perfectly matching components that leaves a high degree of flexibility for customization. The following chapters describe the SESS system concept with its components and functions as well as the control capabilities in comparison to synchronous machines.

A. Scalable system concept for multiple applications

Fig. 1 shows the main system components of the SESS. It consists of a Medium Voltage Power Station (MVPS), a turnkey container solution including an integrated Sunny Central Storage (SCS) inverter with enhanced grid forming and dedicated overload capabilities, a medium voltage step-up transformer and a medium voltage switchgear as pre-installed components for easy transport and quick commissioning. At its DC terminals the MVPS is connected to an external battery storage with an integrated battery management system. A high-performance Power Plant Manager as plant controller observes and controls the power at point of connection to the grid and manages the state of charge of the batteries within the whole power plant.

1) Voltage behind an impedance topology

A closer examination reveals that in grid forming operation each MVPS has electrically the same voltage behind an impedance structure like synchronous machines. Here, grid forming inverters provide and control the voltage, that is equivalent to the excited, inner machine voltage, while the MV transformer represents the current limiting decoupling impedance to other voltage sources and to the rest of the power grid (see also Fig. 2). The electro-chemical battery storage substitutes the rotating mass as mechanical storage, providing enough capacity for multiple services.

2) Versatile system expandability

Coupled at its AC terminals, multiple MVPS with external batteries can be scaled up to a multi-megawatt system. In addition, the essential components can easily be extended by additional equipment for being able to provide services like black start, to establish a high voltage level connection or an adequate decoupling to grid for advanced UPS applications [21,22]. In combination with co-located PV, the SESS enables a partly synchronous PV-storage hybrid systems operation in public electricity grids. Retrofitted with a SESS, large-scale PV power plants receive the ability to provide various grid forming services. The Power Plant Manager ideally supports the joint hybrid PV storage operation.

B. *Grid forming control principle and operation modes*

In contrast to rotating machines where the electro-mechanical physics determine the instantaneous voltage vector dynamics and the resulting power response, in inverter-based systems they are mainly defined by control. For accurate service provision at the point of connection (PoC) of the whole power plant a harmonious interaction of all power plant components is essential. Therefore, the synchronous energy storage system is equipped with advanced controls at inverter and power plant level. Fig. 2 depicts the control system architecture of the SESS in a simplified block diagram.

1) *True voltage source control*

The essential **voltage source** behavior of the SESS is provided by a fast and precise control of the inverter output voltage vector U_1. The voltage control objective is to provide a three-phase harmonic voltage waveform with a magnitude, angle, and frequency according to the reference U_1* and by immediate compensation of any disturbances on it.

2) *Instantanous disturbance response behavior*

The voltage source behavior of the inverters and consequently the whole power plant enables the SESS to provide an **instantaneous power response** and energy exchange to grid events, without any delays. The instantaneous current and power flow results corresponding to the voltage difference $U_{12}=U_1-U_2$ between the inverter and the grid voltage. The currents are physically limited in its rate of change and amplitude by the **decoupling impedance** X that is provided among others by the step-up transformers. Fig. 3 depicts the relationships between magnitude difference ΔU, angle difference $\Delta\vartheta$ and active and reactive power P_1,Q_1.

3) *Harmonic voltage waveform control*

To provision an almost undistorted harmonic voltage waveform at the grid forming inverter's terminal automatically acts as a **sink for harmonics and unbalances**, improving the local power quality conditions by compensating currents. Beyond the positive effects of fundamental voltage control on **voltage quality improvement**, the SESS provides an additional active filter capability for damping of selected harmonic frequencies.

4) *Synchronization with highly adjustable response*

For **synchronous operation** of multiple voltage-controlled inverters with the power grid, each voltage source needs to adjust its voltage vector U_1 in voltage, angle, and frequency in response to changing grid conditions, represented by the changing grid voltage vector U_2. Depending on the application or the service to be provided to the network, different types of active and reactive power response to disturbances might be desired or required for effective grid stabilization.

The SESS grid forming solution offers control modes that are capable to provide **static or transient type of instantaneous power response** to stepwise voltage and frequency disturbances. Fig. 4 illustrates the behavior of the two different response types. A static power response persists if the disturbance continues to exist. A transient power response decays after a specified time, according to the control setting. Thereby, both types of response are provided instantaneously, without delays. Furthermore, the control modes provide the capability for **individual response adjustment** of voltage and frequency (and active and reactive power respectively). If needed, both response types can be combined. In the following the differences of the control modes are described in detail.

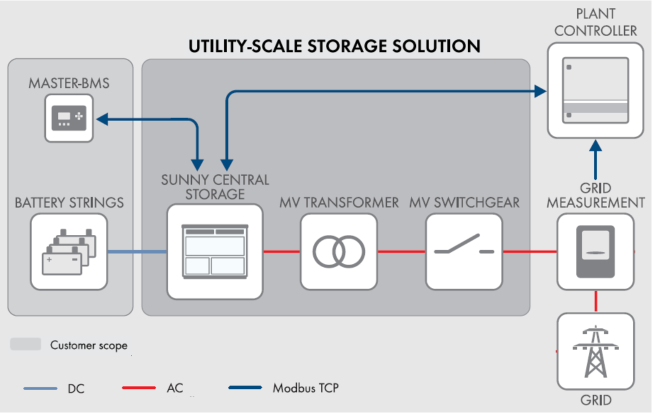


Fig. 1: Fundamental components of the synchronous energy storage system

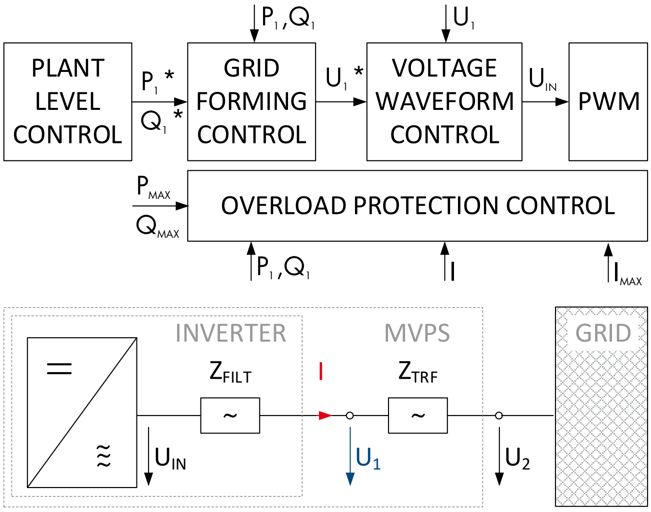
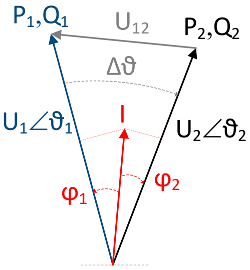


Fig. 2: Simplified block diagram of the SESS control system (top) together with an equivalent electric circuit (bottom)



$$P_1 \cong \frac{U_1 U_2}{X}\Delta\vartheta \qquad (1)$$

$$Q_1 \cong \frac{U_1}{X}\Delta U \qquad (2)$$

Fig. 3: Exemplary illustration of the physical linkage between inverter and grid voltage vectors U_1 and U_2 in respect to the active power P_1 and reactive power Q_1 at inverter terminals shown in eq. (1) and (2)

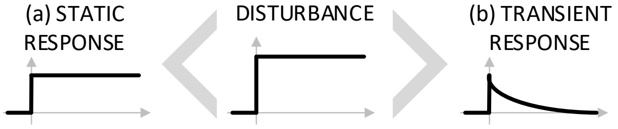


Fig. 4: Exemplary instantaneous static (a) and transient (b) response behavior of a power plant after a stepwise disturbance in the power grid

a) Droop Control for static response

In Grid Forming Droop Control mode the voltage vector is synchronized with the grid without any inertia, by changing voltage and frequency in proportion to inverter load conditions and droop settings. This capability enables multiple parallel voltage sources to immediately find stable voltage and frequency operating points, while managing the instantaneous load power share among the parallel inverters without any communication [23,24]. Through the direct f(P)-linkage between frequency f and active power P and the direct U(Q)-linkage between voltage U and reactive power Q, the instantaneous active power response ΔP is proportional to the frequency deviation Δf from an adjustable nominal value f_N. In analogy the instantaneous reactive power response ΔQ is proportional to the voltage magnitude deviation ΔU from an adjustable nominal value U_N. Eqn. (3) and (4) show the relationships, with nominal apparent power S_N, nominal frequency f_N and droop parameters k_f and k_U:

$$\frac{\Delta P}{S_N} \cong \frac{1}{k_f} \cdot \frac{\Delta f}{f_N} \tag{3}$$

$$\frac{\Delta Q}{S_N} \cong \frac{1}{k_U} \cdot \frac{\Delta U}{U_N} \tag{4}$$

In this operation mode the SESS is capable to provide permanent frequency or voltage containment (primary) reserves without any activation delays. The power and energy response to grid events - that results on top of the plant reference - is determined by droop parameters. Since in this control mode the SESS does not provide any inertia, it is not able to limit the rate of change of frequency (RoCoF) and the rate of change of voltage (RoCoV) of its own voltage vector. Nevertheless, it is capable to contribute indirectly to RoCoF/V reduction of the other voltage sources in the power grid by instantaneously absorbing a proportion of the power imbalance at disturbances. Today, these control mechanisms are successfully applied on remote islands [16], limiting voltage and frequency deviations and gradients even after extreme disturbance scenarios and at very low power system inertia conditions. Another application example is shown in chapter III.

b) Inertia Control for transient response

In Grid Forming Inertia Control mode the SESS is capable to control the RoCoF/V of its own voltage vector directly and individually. Thereby, inertia retards the voltage phasor synchronization in a defined manner, like shown in Fig. 5. The resulting instantaneous active power response ΔP is proportional to the RoCoF (Δf/Δt) and the instantaneous reactive power response ΔQ is proportional to the RoCoV (ΔU/Δt) after a certain settling time, as depicted in Fig. 6 for the RoCoF case (similar behavior is valid for RoCoV). In contrast to the droop-based control, in inertia control mode no static active and reactive power response proportional to frequency or voltage deviations Δf or ΔU is provided but can be added if necessary.

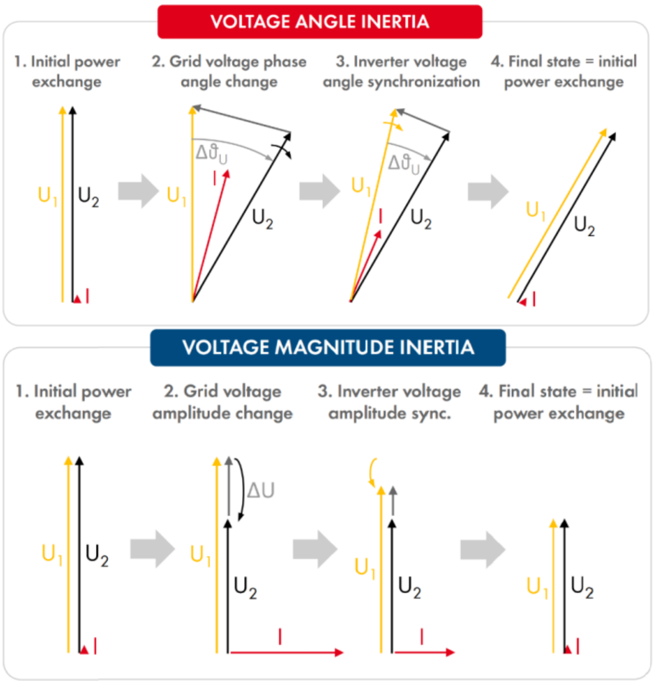


Fig. 5: Illustration of inertial voltage angle and inertial voltage magnitude synchronization control (initial conditions are set to zero for simplicity)

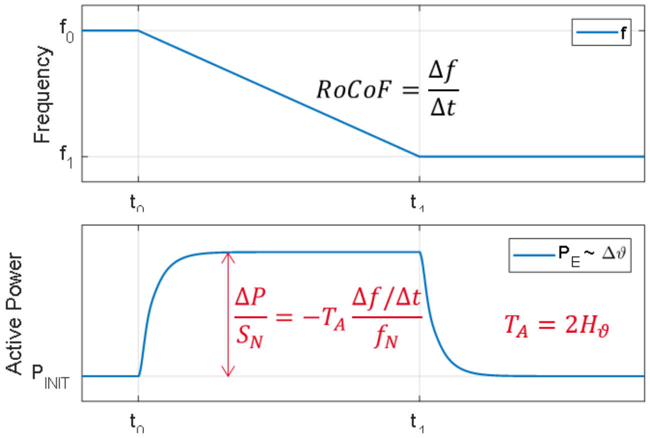


Fig. 6: Inertial response to a constant RoCoF disturbance

With active voltage angle and voltage magnitude inertia modes, the inertial power response - on top of the plant reference - can be adjusted by voltage angle and voltage magnitude inertia constants H_ϑ and H_U (in s). The inertia constants are proportional to ΔP and Δf/Δt as well as ΔQ and ΔU/Δt as per unit values respectively. Equations (5) and (6) show the relationships, with nominal apparent power S_N and nominal frequency f_N:

$$\frac{\Delta P}{S_N} \cong -2 \cdot H_\vartheta \cdot \frac{\Delta f/\Delta t}{f_N} \tag{5}$$

$$\frac{\Delta Q}{S_N} \cong -2 \cdot H_U \cdot \frac{\Delta U/\Delta t}{U_N} \tag{6}$$

The main advantages of Grid Forming inertia provided by the voltage-controlled SESS, compared to df/ft-based inertia emulation with current-controlled grid following inverters [25,26], is the direct RoCoF/V control of the own voltage vector without need for frequency measurement. The resulting instantaneous response (<5 ms) immediately counteracts the power imbalance, reducing the need for other voltage sources in the grid to change their voltage vector position for synchronization. This behavior allows to limit the RoCoF/V without any delays and directly after grid events but requires an amount of power and energy reserves for action. The amount of required reserves highly depend on the disturbance level but also on the inertia constant and damping settings. Due to its transient, decaying nature the inertia response requires a manageable portion of energy.

5) *Subsynchronous oscillation damping*

The mechanical or electrical inertia [24] introduces additional system dynamics, that counteracts to the synchronization of the voltage vector with the grid. If not adequately damped, this counteraction can cause weakly damped oscillations of the inverter voltage vector U_1 with other voltage sources in the grid. This damping also depends on the decoupling impedance between the voltage sources. For effective damping provision that covers the needs of different applications, the Grid Forming Inertia Control mode of the SESS provides a number of **damping control options**, including load imbalance feedforward damping as well as voltage or frequency feedback damping. In general, a higher damping of the voltage vector dynamics is beneficial for the stability of the SESS and for the local power system stability. On the contrary, damping impacts the synchronization and the resulting power and energy flows. Consequently, a careful choice of the damping parameters aligned with decoupling conditions on site is recommended.

6) *Overload protection*

The control system of the SESS provides **advanced hardware and software overload protection** mechanisms with a harmonized coordination between the grid forming inverters and plant controls. Depending on the dynamics of the load that follows the disturbance, different mechanisms come into play, including the fast pulse-width limiting HW protection, voltage vector manipulation (via virtual impedance) and power control, with adjustment possibilities for maximum active and reactive power limits [16,27]. These mechanisms allow to ride-through major grid events with maximum possible grid support.

IV. APPLICATION EXAMPLES

The versatile capabilities of the SESS provide the opportunity for local and global stabilization of voltage, angle, and frequency in power grids. The following selected laboratory test results give an insight into how the SESS can be used for the provision of advanced grid forming services for a variety of applications.

A. *Frequency stabilization with reduction of frequency deviation, RoCoF and vector shift*

There is an increased risk for generator and load disconnection in consequence of high RoCoF, frequency deviation or vector shift events, in power grid areas with a reduced number of synchronous generators with inertia from rotating mass. Angular shifts, frequency gradients and frequency deviations can be reduced with solutions that are capable to directly control the angle and frequency inertia and with solutions that are capable to provide an instantly compensating power to reduce the power imbalance like e.g. delay-free frequency containment reserves (FCR). As presented in chapter III, the synchronous energy storage system is capable to provide both, inertia and delay-free FCR individually.

For control mode comparison and capability demonstration laboratory tests with a focus on the reduction of frequency deviation and RoCoF have been performed with a test setup shown in Fig. 7. The test setup represents a downscaled power system that incorporates all relevant grid stabilizing mechanisms that are present in a large-scale low-inertia power system with a high share of inverter-based sources. Thereby, the 462 kVA Diesel Genset represents the conventional synchronous machine-based generation, that provides inertia, frequency containment and frequency restoration services to the grid. The inertia constant of the Diesel genset is $H_\vartheta \approx 0.65$s and was estimated by the initial RoCoF measurement at load step tests in respect to Eq. (5). The SCS 2200 Grid Forming inverter demonstrator with a downrated power of 500 kVA represents the power electronic SESS, that can be operated in different control modes for laboratory tests. For simulation of a large power imbalance scenario a 60 kW load (approx. 13% in respect to the Diesel Genset power rating) was connected to the grid. This scenario was repeated for different inverter control modes including:

- grid following current-controlled mode without any grid supporting functions,
- grid following current-controlled mode with frequency containment reserves provided by the plant controller (droop slope of -0.1 pu/Hz with rise time of 2 s from frequency step to 90% active power),
- grid forming voltage-controlled mode with droop control (-0.4 Hz/pu) and
- grid forming voltage-controlled mode with inertia control ($H_\vartheta \approx 25$s).

The results for frequency response and the active power responses of the Diesel genset as well as the SCS inverters are shown in Fig. 8.

In grid following (GFL) control mode without any frequency supporting control and with a grid synchronization via PLL, the inverter does not provide any inertial response that could contribute to RoCoF reduction. Because the Diesel genset need to compensate the whole power imbalance, its frequency RoCoF≈-5 Hz/s and the frequency Nadir≈48.9 Hz are very large. $\Delta P(\Delta f)$ frequency containment reserve (FCR) provision by the plant controller in grid following mode of the inverter starts to counteract to the frequency change only with substantial response delays, producing some decaying oscillations. Thereby, the frequency deviation is reduced to a Nadir of 49.2 Hz.

In grid forming (GFM) droop control mode FCR response is provided instantaneously without any delays, thereby largely relieving the genset from decelerating load. Here, the frequency deviation is kept very small with a Nadir of 49.95 Hz, without notable oscillations. Due to its static nature, the amount of energy exchange depends also on the activation time of frequency and voltage restoration reserves, if not reduced by control before. In grid forming inertia control mode an inertial response is provided instantaneously without any delays, also here largely relieving the genset from initial decelerating load for a specified transient period, keeping the amount of energy exchange limited. Due to high inertia constant settings the frequency only decreases to 49.74 Hz and the RoCoF is reduced to 0.12 Hz/s.

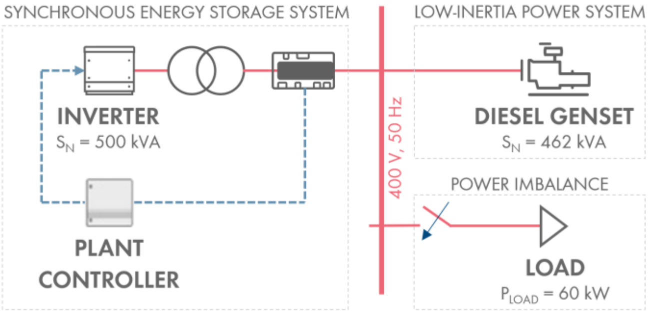


Fig. 7: Laboratory setup for demonstration of SESS control capabilities

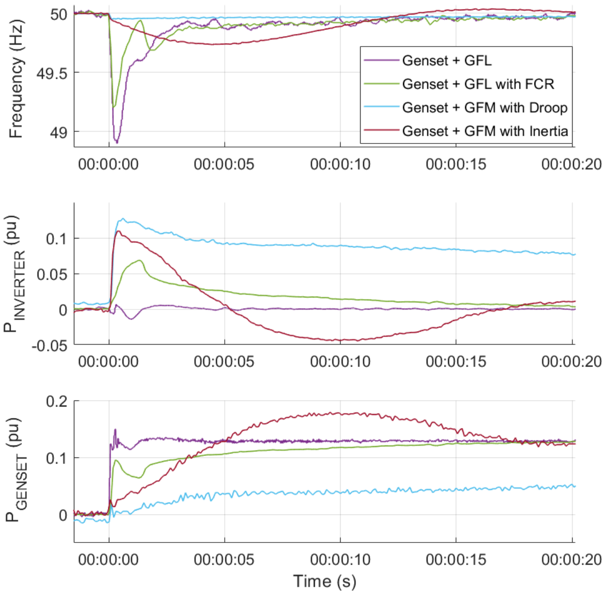


Fig. 8: Impact of different inverter system control modes on the frequency of a downscaled low-inertia power system at a power imbalance event

B. *Synchronous fault current provision*

For adequate fault protection and highest possible grid support during faults the short-circuit levels (or fault levels) need to be maintained above a minimum level in different parts of the power grid. Synchronous fault current can be provided by synchronous energy storage systems in similar manner like with synchronous generators. Fig. 9 shows the results of a laboratory tests for a phase to ground fault at inverter demonstrator terminals in comparison to EMT simulations. The result demonstrates the instantaneous current response, that is limited to the maximum capable level of the inverters and shows good alignment of the measured and the simulated voltage and current values.

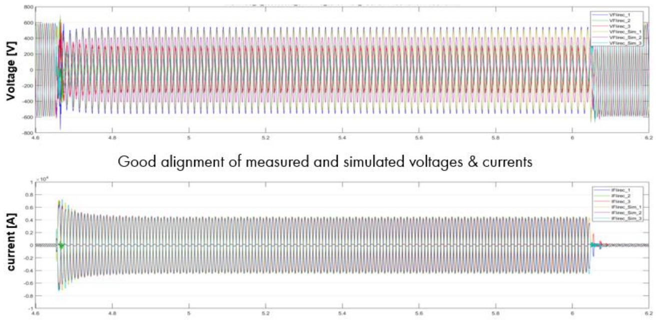


Fig. 9: Comparison of measurement and simulation results for synchronous fault current provision of an SCS inverter demonstrator under 1ph to ground fault conditions

C. *System strength increase in weak grids*

System strength is a measure of the ability of a power system to remain stable under normal conditions and to return to a steady state condition following a system disturbance [28]. Under weak grid conditions, especially in power system areas with a very high share of grid following generation and very low synchronous generation at the same time, unwanted controller interactions may lead to harmful network oscillations, once they are excited. System strength shortfalls can constraint renewable generators and delay their grid connection. As described in [29,20], inverter-based grid forming solutions have the potential to make renewable generators more independent from system strength. With its inertia, droop and damping control capabilities the SESS can effectively increase system strength and short-circuit level, without the need to rely on synchronous generators or condensers as traditional solutions. Fig. 10 demonstrates the capability for system strength improvement based on a laboratory test with the same setup as for RoCoF reduction (Fig.7). Therefore, the SESS was initially operated in grid following mode in parallel to the Diesel genset, that was supplying the 60 kW load at steady state. At low load conditions the Diesel genset has difficulties to stabilize its voltage angle and frequency. The resulting frequency oscillation amplitudes were in the range of ±30 mHz. Switching to grid forming inertia control and increasing the angle inertia constant from 0.5 to 25 s reduced the frequency and angle oscillations, proving an increased system strength.

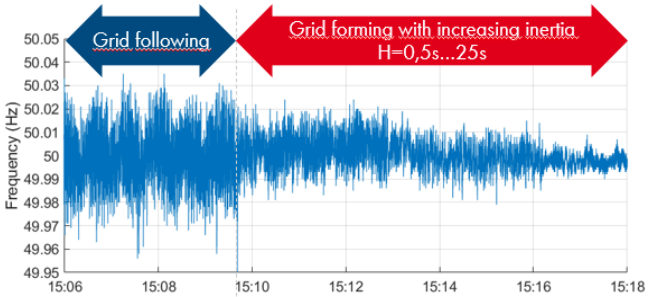


Fig. 10: System strength improvement by grid forming inertia provision

D. *Response to subsynchronous oscillations*

With its grid forming droop, inertia and damping control the SESS is capable to provide an instant power response to sub-synchronous voltage, angle, and frequency oscillations. The response characteristic depends on the control mode and the parameter settings. Fig. 11 exemplarily depicts the response of the SESS under different control mode settings. The tests have been performed under the laboratory setup similar to Fig. 7, where the Diesel genset was disconnected from the grid and replaced by an artificial voltage-source that provided an ideal voltage with a frequency that was oscillating around 50 Hz with a period of 1 sec and an amplitude of 0.2 Hz (open loop test). The measurement results indicate that in grid following mode, without any grid supporting functions being active, the inverter system does not provide any response to frequency oscillations. Whereas in grid forming droop control mode the power response is (according to eq. (3)) proportional to the frequency deviation, increasing its power when the frequency decreases and vice versa, without any delays. In grid forming inertia control mode the power response is proportional to the rate of change of frequency, having its maxima near to the zero crossing of the frequency oscillation. An additional phase shift is a result of the damping settings.

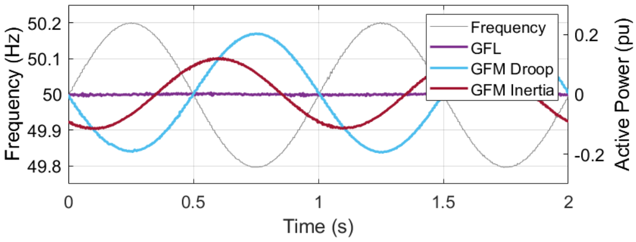


Fig. 11: Comparison of sub-synchronous frequency oscillation response behavior for grid following (GFL), grid forming (GFM) droop and grid forming inertia controls of the SESS

E. Voltage quality improvement by harmonic damping

The advanced voltage waveform control and active harmonic filter capabilities of the SESS demonstrator enable an effective improvement of the local AC voltage quality. For the demonstration of the positive impact on the voltage distortion reduction, voltage and current harmonic measurements were performed under different operating conditions with the test setup shown in Fig. 7. The test results for the sequential test are shown in Fig. 12 exemplarily for the 5th and 7th harmonics. Between t_{OFF} and t_{GFM} the inverter was disconnected from the downscaled power system. The connection of the SESS demonstrator in voltage-controlled grid forming mode to the experimental test system significantly improves the 5th and 7th voltage harmonics. By doing this, it acts as a sink for harmonic currents. Additional activation of active harmonic filtering at t_{GFM+AF} allow for further damping of the voltage harmonics by extended harmonic current compensation.

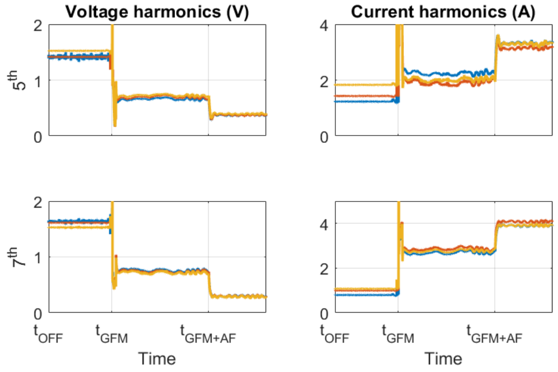


Fig. 12: Voltage harmonic damping under different operating modes of the SESS demonstrator (three phase voltages and currents are shown)

V. CHALLENGES AND NEEDS

For establishing advanced grid forming solutions such as the synchronous energy storage system presented in this paper, power plant designer and manufacturers face multiple challenges. In order to develop systems that provide the needed characteristics effectively, it is necessary to understand the control objectives and scenarios of interest. In the recent years, this has been addressed, e. g. in [32,33]. However, further work is needed to specify the needs and requirements more precisely.

A. Need for realistic grid event scenarios for the design of grid forming capable inverter-based power plants

In contrast to grid following systems, the design of grid forming systems like the SESS, with focus on angle, voltage, and frequency stabilization beyond the normal operation, requires design considerations regarding the required power and energy reserves, that highly impact the costs and the profitability of a project. For being able to estimate the required power and energy storage amount and to design profitable solutions, there is a need for realistic but also reasonable worst-case scenarios and load profiles that need to be covered in grid forming manner. This can include:

- worst-case RoCoF/V events without hitting capability limits,
- worst-case RoCoF/V events to ride through,
- worst-case voltage angle and magnitude change events to ride-through,
- worst-case fault durations to ride-through.
- worst-case load steps to be covered, keeping a limited frequency deviation

Often such information can only be provided by system operators for particular grid connection points.

B. Need for a grid forming technical specification

Even if there are first technical specifications for inverter-based grid forming systems [12], the advantageous behavior of grid-forming inverters in public grids is currently often inhibited by some of the technical rules for grid-connected operation [16], either because they were written with a background of grid following controlled DER or due to conflicting objectives (e.g. unintentional islanding detection). Power electronic interfaced power plants are usually classified to be “non-synchronous” sources, even if they have grid forming capabilities to operate synchronously to other voltage sources such as synchronous machines. An internationally harmonized requirem. specification catalogue for grid-forming is needed, particularly regarding to the

- evidence of grid-forming behavior,
- fault-ride-through behavior,
- behavior at operational limits of the inverters,
- prevention of unintended islanding,
- characterization of inverter-based inertia and
- common test procedure and quality criteria.

C. Need for a regulatory and technical minimum requirements framework

From a system perspective, it’s not necessary, that all generators have a grid forming behavior. This is evident, since already today there is a high share of “non-synchronous” generation. Of course, such limits highly depend on the disturbance scenarios that shall be able to be handled and also on the control behavior of the non-synchronous generators [31,34]. Even though modern renewable generators still rely and depend on voltage and frequency forming sources, they provide a lot of grid stabilizing functions, that enable their increased integration into power grids. By developing (and utilizing) those capabilities further towards operation in low inertia and low SCR (Short Circuit Ratio) grids, a significant share of non-synchronous generation can be accepted also in the future. Renewable power conversion technology is usually designed and optimized with the focus on cost-effective energy generation, its efficient conversion, and precedential grid injection. On the other hand, for purposes of frequency containment or energy shifting, or innovative approaches like "Grid Boosters [8]", large storage plants are on their way to the grid anyway. Therefore, grid forming capabilities as well as an obligation for power and energy reserves for all inverter-based generators are not necessarily crucial and even uneconomical, if grid forming capabilities are provided at sufficient scale by other equipment installed in the grid. In the transition phase, where grid forming services are inherently provided by synchronous generators, a regulatory framework with economic incentives for grid forming capable services (such as the "Stability Pathfinder" program in GB) could stimulate the technological progress of advanced grid forming systems and accelerate their integration into power systems with a continuously increasing renewable share. Based on this experience, specifications for generators may be derived, that take technology-specific constraints into account and lead to a cost-efficient overall power system [30].

VI. CONCLUSION

For a successful power system transition towards a more carbon-free electricity generation mainly from renewable sources, there is a need for enhancement of the grid stabilizing mechanisms especially in network regions with very low synchronous generation running. The integrated and matching SESS solution provides a set of powerful grid forming capabilities for effective stabilization of angle, voltage, and frequency in electric power systems at transmission and distribution level. It can easily be combined with renewable sources like PV for being able to provide versatile grid forming services for various applications in public power grids. Results from extensive field tests, laboratory measurements and accurate EMT simulations demonstrate the enormous potential of these technology to support or completely replace rotating machines. For an accelerated integration of grid forming systems into electricity grids and their utilization in various applications, there is a development need for internationally harmonized technical specifications, reasonable design scenarios and a regulatory framework including economic incentives.

ACKNOWLEDGMENT

Parts of the results presented in this paper were obtained within the projects „Grid Control 2.0 – Control and Stability in Inverter Dominated Interconnected Systems" (0350023D) and "PV Diesel Global" (03EE1091A). We acknowledge the support of our work by the German Ministry for Economic Affairs and Energy and the Projektträger Jülich within the projects. Only the authors are responsible for the content of this publication. This paper does not reflect the consolidated opinion of the mentioned project consortia.

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