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International Energy Agency
Photovoltaic Power Systems Programme

Task 14 Solar PV in the 100% RES Power System

PVPS

Provision of frequency related services from PV systems

2024

Report IEA-PVPS T14-17:2024

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What is IEA PVPS Task 14?

The objective of Task 14 of the IEA Photovoltaic Power Systems Programme is to promote the use of grid-connected PV as an important source of energy in electric power systems. The active national experts from 15 institutions from around the world are collaborating with each other within Subtask B – Operation and planning of power systems with high penetration of Solar PV and RES – in order to share the technical and economical experiences and challenges. These efforts aim to reduce barriers for achieving high penetration levels of PV Systems in Electricity Grids.

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Authors

- **Main Content:** Gunter Arnold (Fraunhofer IEE)
- **Chapter 4.1:** Adolfo Anta, Peter Jonke, Roland Bründlinger (AIT)
- **Chapter 4.2:** Gunter Arnold, Siddhi Shrikant Kulkarni, Nils Schäfer (Fraunhofer IEE)
- **Chapter 4.3:** Giovanna Adinolfi, Giorgio Graditi (ENEA)
- **Chapter 4.4:** Yuzuru Ueda (Tokyo University of Science), Yuka Ogasawara (NEDO), Eitaro Omine (NEDO)
- **Chapter 4.5:** Takashi Oozeki (National Institute of Advanced Industrial Science and Technology (AIST), Yuzuru Ueda (Tokyo University of Science)

- **Editor:** Gunter Arnold (Fraunhofer IEE)

INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA PVPS Task 14

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LIST OF ABBREVIATIONS

AC	Alternating Current
ACER	European Union Agency for the Cooperation of Energy Regulators
BESS	Battery Energy Storage System
CE	Continental Europe
CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resource
DRTS	Digital Real-Time Simulation
DSO	Distribution System Operator
EHV	Extra High Voltage
EMT	Electromagnetic Transient
ENTSO-E	European association for the cooperation of transmission system operators for electricity
ESM	Energy Storage Module
EU	European Union
IBR	Inverter Based Resources
IEA	International Energy Agency
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
GFI	Grid Forming Inverter
GFL	Grid Following
GFM	Grid Forming
LFSM-O/U	Limited Frequency Sensitive Mode Overfrequency/ Underfrequency
LV	Low Voltage
MV	Medium Voltage
PHIL	Power Hardware in the Loop
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RES	Renewable Energy Sources
ROCOF	Rate of Change of Frequency

RR	Replacement Reserve
SI	Synthetic Inertia
TSO	Transmission System Operator
UCTE	Union for the Co-ordination of Transmission of Electricity
VER	Variable Energy Resources
VSM	Virtual Synchronous Machine
WEO	World Energy Outlook
WT	Wind Turbine

EXECUTIVE SUMMARY

Solar PV in combination with Windenergy and dispatchable Renewable Energy Sources are becoming globally the most important energy sources for the future electricity supply and the share of fossil fuelled bulk power plants with rotating generators will decrease strongly. Thus, solar PV systems as well as other inverter coupled generators (e.g. Windturbines) and storage units must take over additional grid supporting tasks of conventional power plants in order to allow for secure and stable operation of electrical power systems at all times.

This report aims to present the status and the potential of distributed solar PV and PV hybrid systems with respect to provision of frequency related services. Very large PV systems, which must be connected directly to bulk power systems (e.g. to EHV level) and its specific requirements are not considered in this report.

Due to a wide range of technical and economic advantages, Alternating Current (AC) technology has become established worldwide for public electrical power supply over the past 150 years. In order to keep the grid frequency in such AC power systems stable, it is mandatory to assure an electrical active power balance in the entire supply area, i.e. to adjust at any time the active power generation to its demand. PV systems with its capability to adapt its active power generation can thereto contribute very well to frequency stabilisation, although they have certain limitations such as dependency on solar irradiation, response speed or fast frequency measurement.

Depending on the legal background of the electricity supply and especially the power system market design in the various countries, the frequency control / balancing energy products specifications and designations are different, but the physical principles in the background are equivalent. In the European Union five different power balancing / frequency control services/products have been defined and traded on the power balancing markets:

a. Operating or Spinning Reserve

b. Frequency Containment Reserve (FCR) or primary control reserve

c. Automatic Frequency Restoration Reserve (aFFR) or secondary control reserve

d. Manual Frequency Restoration Reserve (mFFR) or tertiary control reserve

e. Replacement Reserve (RR)

With increasing share of PV power its importance for securing a stable power system frequency has become obvious and the development and implementation of frequency related grid code requirements for PV systems in various countries took place during the last 10 to 15 years.

The automatic reduction of active power feed-in of PV systems in case of overfrequency situations, so-called Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) was introduced in some countries since more than 15 years and is nowadays a mandatory requirement for all PV systems in nearly all European countries and beyond.

Simultaneously with the strong increase of grid connected stand-alone Battery Energy Storage Systems (BESS) or combined PV-BESS systems requirements for the automatic increase of active power feed-in during underfrequency events – Limited Sensitive Mode-Underfrequency (LFSM-U) were developed and implemented in the latest network codes of different countries.

PV Systems already today have the technical capabilities to provide various frequency related grid services: Reduction of active power generation in case of overfrequency and – in combination with BESS – automatic increase of their output in case of underfrequency.

Furthermore, Frequency Containment Reserve (FCR) is an important frequency support service. Although this feature is procured on balancing markets, its specification has been introduced in some network codes, for instance like in the German HV network code for connection of generators.

The transition from grid-following to grid-forming operation – already foreseen in upcoming revisions of selected grid-codes – will enable PV systems to provide the full set of frequency services, analogue to services today provided by rotating generators.

Power system stability studies from Transmission System Operators have clearly shown, that during the next years and decades the probability for the provision of pre-defined inertia constant is decreasing and the time periods with less than this inertia value are strongly increasing. Thereto, it is especially in low inertia and inverter dominated power systems absolutely necessary, that any active power imbalance would be reduced as soon as possible by means of activating very fast active power reserves, such as Synthetic Inertia (SI) or Fast Frequency Response (FFR). They are currently not mandatory requested in Grid codes, but in the current draft of the lately revised European grid code Requirements for Generators (RfG) from 2023 both requirements are foreseen for inverter coupled power stations with rated capacities exceeding certain limits.

The case studies presented in this report successfully demonstrate the capabilities of Solar PV to provide a wide range of frequency related services in real-world power systems environments.

The five selected projects/case studies have clearly demonstrated that PV Systems solely or esp. in combination with BESS are able to provide different types of frequency related grid services.

PV systems equipped with grid following PV inverters must contribute to certain services such as the reduction of active power generation in case of overfrequency situations (LFSM-O). In combination with Battery Electric Storage Systems (BESS) they are also often requested to increase their active power output if an underfrequency event occurs (LFSM-U).

Furthermore, it can be stated that the LFSM-O/U response times of PV inverters and BESS systems are remarkable shorter compared to rotating generating units such as steam plants or CHP units. This short response times allows PV and BESS systems in principle to contribute to Fast Frequency Response (FFR).

The emulation of intrinsic inertia of synchronous generating units and rotating loads using the grid coupled power inverters of RES power stations is often called Synthetic Inertia (SI). This is one of the most important capabilities of Grid Forming Inverters (GFI) and provides nearly instantaneously active power proportional to a frequency gradient (ROCOF) value.

The provision of fast frequency services and synthetic inertia by PV systems (with or without batteries) will become very important in near future, especially in supply areas which are dominated by inverter coupled generators.

Clearly and precisely stipulated requirements as well as standardized testing procedures are a key for compliance assessment of different PV systems and for comparison of its contributions to frequency related services.

Fast frequency services by PV systems using grid following inverters are currently either a mandatory requirement for large PV Plants connected to HV or EHV networks or on the other hand could optional be offered on power balancing markets (depending on power market design).

A similar approach (grid code requirement and participation on the power balancing market) would be also suitable for the introduction and implementation of the very fast frequency services of grid forming inverters (GFI) such as Synthetic Inertia (SI) provision.

Concluding it can be said that the results of the described case studies are promising, but further research and demonstration projects are necessary esp. for implementation of these frequency related services, which come along with Grid Forming Inverters (GFI).

1 INTRODUCTION

In several countries, such as Australia, Spain, Greece, Honduras, Netherlands, Chile, Germany, Japan and Italy, the installed PV systems can provide about 10 % of the total electricity demand (theoretical PV penetration 2021 in [1]). The highest share is determined in Australia with a theoretical penetration level of more than 15 %, followed by Spain and Greece with around 14.2% and 13.6% respectively [1]. Overall, PV generation covers about 5% of the electricity demand worldwide. The PV penetration in many countries is growing rapidly. According to the different Scenarios (STEPS, APS and NZE) of the IEA world energy outlook 2022 (WEO 2022) [2], PV will become the largest source of installed generation capacity before 2030 (see Figure 1). With respect to global electricity production, PV will reach a share of about 12 % in the Stated Policies (STEPS) Scenario and about 20 % in the Net Zero Emissions (NZE) Scenario of WEO 2022 [2] in the year 2030. The rapid growth of solar PV is not only driven by policy support but also by improved competitiveness of solar PV and the increasing prices of fossil fuels [2].

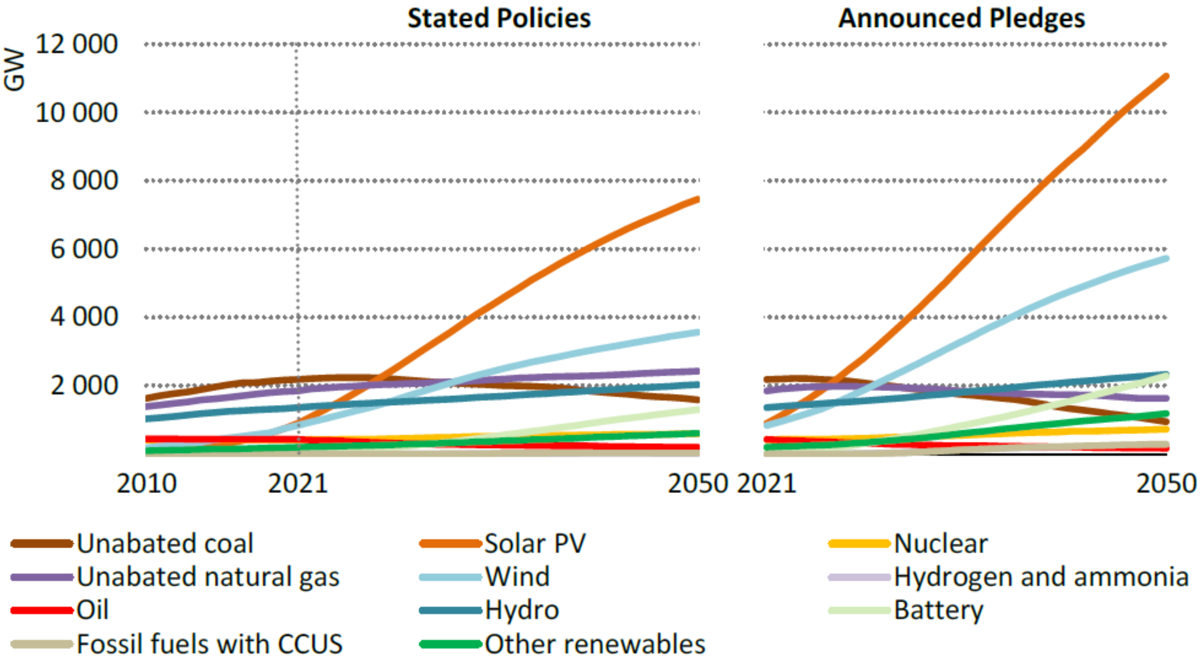

Figure 1: Global power generation capacity by source in the Stated Policies Scenario and the Announced Pledges Scenario of the IEA World Energy Outlook 2022 [2]

According to the WEO 2022 [2] PV in combination with Windenergy and dispatchable Renewable Energy Sources (such as Hydro and Biomass) are becoming globally the most important energy source in the future electricity supply and the share of fossil fuelled bulk power plants with rotating generators will decrease strongly. Thus, solar PV systems as well as other inverter coupled generators and storage units must take over additional grid supporting tasks of conventional power plants in order to allow for secure and stable operation of electrical power systems at all times by providing so-called “ancillary services”. The main objectives of ancillary services includes to control the power system voltage and frequency not only during normal operation but also during system faults. Traditionally, Transmission System Operators (TSO) are responsible for this and depending on the power market design the various measures for voltage and frequency control are mainly procured on power system markets.

Simultaneously with the increasing penetration of renewable energy systems (RES) and PV systems, the grid codes in the affected areas (countries) and on the different voltage levels were adapted step-by-step and more sophisticated power plant capabilities were demanded even from smaller generators.

In conjunction with/ as a consequence of the refined grid code requirements for generators especially inverter for PV, storage and other RES have achieved significant technological developments during the last 15 to 20 years.

This report aims to present the status and the potential of distributed solar PV and PV hybrid systems with respect to provision of frequency related services. The specific requirements of very large PV systems, which need to be connected to bulk power systems (e.g. to EHV level) are not considered. Subsequent to an introduction of the various measures in the context of frequency control, it provides an overview of corresponding grid code requirements. The main chapter of this report contains a collection of uses cases (field experiences and laboratory results) from different IEA PVPS countries. The target groups of this publication are especially grid operators and decision-makers, which may not be aware of the state of the art and the potential of PV and PV hybrid systems with respect to provision of frequency related services. The main focus of this report is to give an overview in the context of frequency related services and to introduce exemplarily good practices of distributed PV systems from different IEA PVPS member countries.

2 FUNDAMENTALS OF FREQUENCY RESPONSE

In this section an overview about the fundamental physical relations between network frequency and active power balance will be provided. Furthermore, the different frequency services (provision of active power reserve) will be introduced and explained.

2.1 Frequency control and active power balance

Due to a wide range of technical and economic advantages, alternating current (AC) technology has become established worldwide for public electrical power supply over the past 150 years.

In conventional large-scale power plants with rotating drive units for the generation of electrical energy and for grid forming, directly grid coupled synchronous generators are still generally used. Due to their design, synchronous generators have a rigid coupling between mechanical speed and electrical grid frequency.

Provided that all synchronous generators in a delimited supply area operate within their natural stability limits, that they are able to be operated at their synchronous speed and to exchange synchronizing power among themselves, it is possible in undisturbed operation to notice the same network frequency everywhere in an arbitrarily extended AC electricity supply system.

For a stable operation of any electric power supply system, it is therefore necessary to support the natural tendency of synchronous generators to maintain synchronism and synchronous speed through the use of closed-loop control.

Thus, a direct correlation between grid frequency and active power balance can be determined even for arbitrarily extended AC electricity supply systems.

In order to keep the grid frequency constant, it is therefore in AC power supply systems mandatory to adapt at any time the electrical energy consumption P_{Load} and Generation P_{Gen}.

- Imbalance of Active Power Generation P_{Gen} and Consumption P_{Load} has an instant impact on grid frequency
    a) $P_{Gen} = P_{Load} \rightarrow f_{Grid} = \text{const.}$,
    b) $P_{Gen} > P_{Load} \rightarrow f_{Grid} = \uparrow$ and
    c) $P_{Gen} < P_{Load} \rightarrow f_{Grid} = \downarrow$
- Various Possibilities to influence the grid frequency
    - In case of an Active Power surplus (b) the Generation needs be reduced (b.1) or the Consumption should be increased (b.2) and
    - If an Active Power deficit [c] occurs, it is necessary either to increase the Generation (c.1) or to reduce the Consumption (c.2).

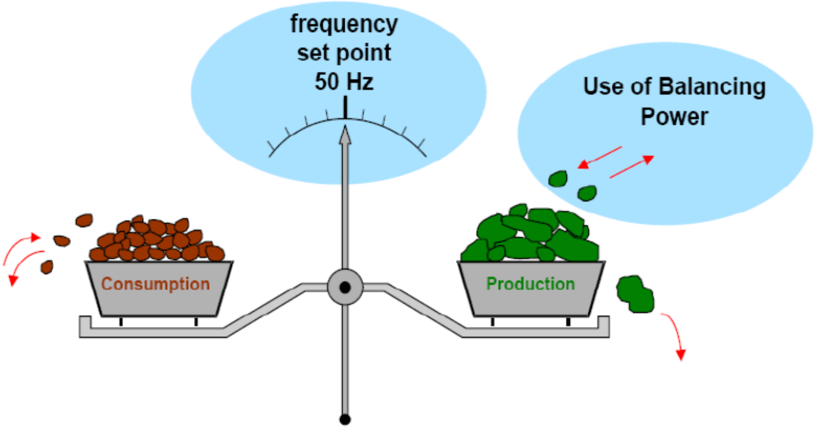

Figure 2: Principle of Frequency Control by Use of Active Power Balancing [3]

As it was already explained, a deficit in active power generation will cause an instantaneous drop of power system frequency, which mainly depends on the ratio of the active power imbalance, the overall inertia of the power system and the frequency control actions for re-establishing the active power balance.

Frequency events/disturbances could be characterized by various parameters:

- Initial Frequency Gradient or Rate of Change of Frequency (ROCOF),
- Largest dynamic frequency deviation from nominal value, esp. for frequency drops it is the so-called frequency nadir and the
- Steady state frequency deviation

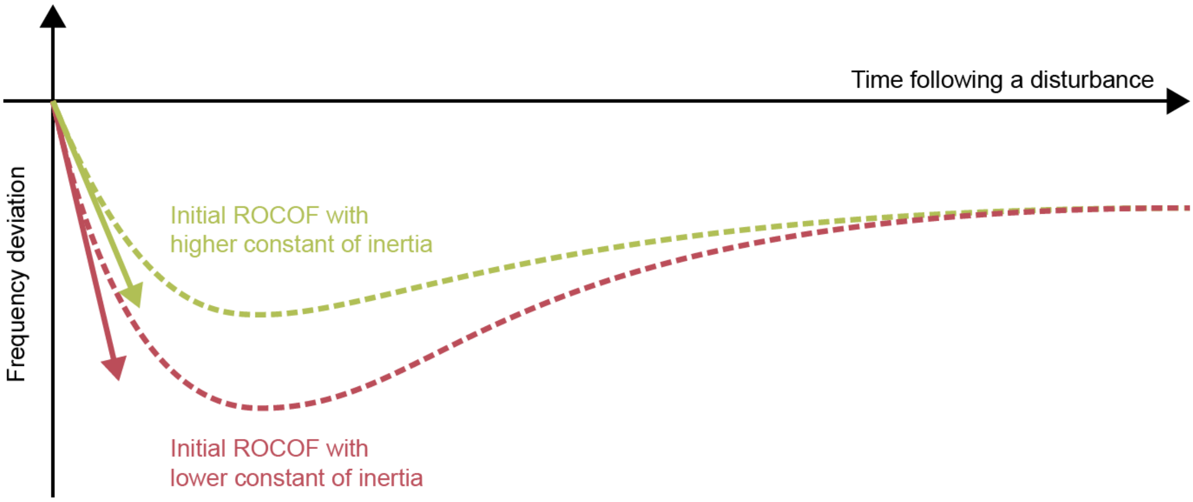

Figure 3: Time response of two exemplary frequency events depending on inertia [4]

2.2 Overview of Frequency control services

In this section a short overview of the different frequency control services, its purposes and typical time intervals will be presented. This overview is based on the reserve power market framework in the European Union (EU), which is legally based on different EU commission regulations, such as

- EC REGULATION 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation [5] and
- EC REGULATION 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing [6].

Depending on the legal background of the electricity supply and especially the power system market design in the various countries, the frequency control / balancing energy products specifications and designations are different, but the physical principles in the background are equivalent.

Figure 4 provides an overview of different frequency control services in the European Union and its typical time intervals.

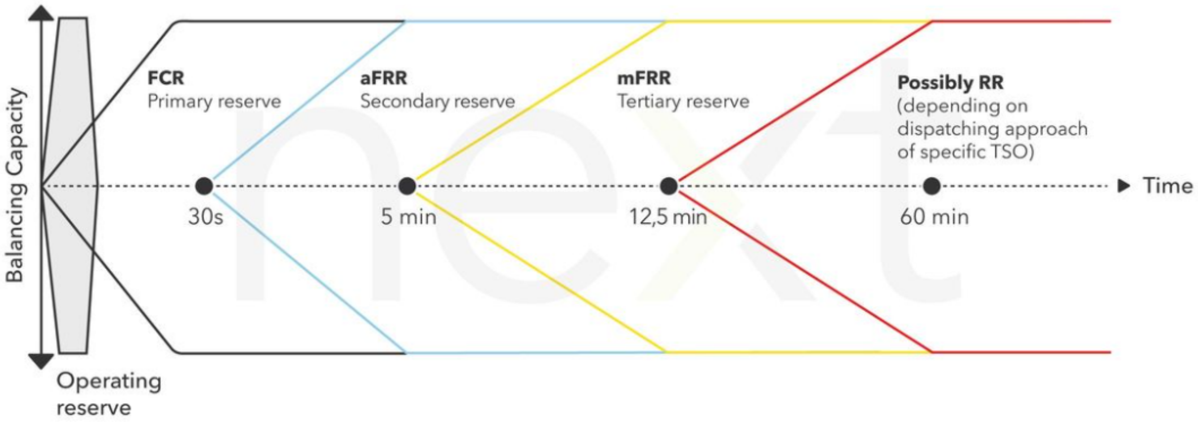

Fig. 4: Overview of different frequency control services in the EU and its typical time intervals [7]

5 Different power balancing / frequency control services with its specific time intervals are defined in the European Union:

- Interval 1: (0 - 5 sec.); **Operating or Spinning Reserve**, Self-regulation effect: Decrease of grid frequency and mech. speed; → Release of Rotating energy of all rotating systems.
- Interval 2: (0 - 60 sec.); **Frequency Containment Reserve (FCR) or primary control reserve**, With the turbine governor the prime mover power of the primary regulating power plants will be increased; $P_{Gen} = P_{Load}$ → Grid frequency decrease is stopped
- Interval 3: (30 sec. - 12.5 min.); **Automatic Frequency Restoration Reserve (aFFR) or secondary control reserve**, the power output of the Secondary regulating plants will be adapted; → Remaining Frequency Offset will be eliminated.
- Interval 4: (5 min. - 1 hour); **Manual Frequency Restoration Reserve (mFFR) or tertiary control reserve** targets to restore an adequate secondary control reserve for the balancing area and the defined balancing time interval (15 min – 60 min)
- Interval 5: (12.5 min - few hours); **Replacement Reserve (RR)** depending on TSO specific approach.

3 FREQUENCY RELATED GRID CODE REQUIREMENTS FOR PV SYSTEMS

This section will provide a short overview about frequency related grid code requirements in different IEA PVPS member countries with relevant shares of installed PV power.

3.1 State of the art

With increasing share of PV power its importance for securing a stable power system frequency has become obvious and the development and implementation of frequency related requirements for PV systems in various countries took place during the last 10 to 15 years. The following publications are providing comprehensive overviews on the evolution of grid code requirements for PV systems especially in the European Union [8], [9]. In contrast to [8] and [9], which are focusing on the European network code "Requirements for Generators" (EC REGULATION 2016/631) [10], paper [11] and [12] cover also country specific network regulations for PV or PV-BESS systems later than 2016 from Europe and abroad (US, Australia).

Based on the aforementioned publications it can be stated that especially the automatic reduction of active power feed-in of PV systems in case of overfrequency situations, so-called Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) was introduced in some countries since more than 15 years and is nowadays a mandatory requirement for all PV systems in nearly all European countries according to the European network code "Requirements for Generators" [10].

Simultaneously with the strong increase of grid connected stand-alone Battery Energy Storage Systems (BESS) or combined PV-BESS systems requirements for the automatic increase of active power feed-in during underfrequency events – Limited Sensitive Mode-Underfrequency (LFSM-U) were developed and implemented in the latest network codes of different countries, such as US, Australia and Germany.

Frequency Containment Reserve (FCR) is an important ancillary service, which is procured on power balancing markets in many countries worldwide. Large power generating plants connected to the transmission network levels (HV and EHV) are requested to provide this capability. Although this feature is procured on balancing markets, its specification has been introduced in some network codes, for instance like in the German HV network code for connection of generators [15].

Table 1: Overview of country specific frequency related grid code requirements

Country - Voltage Level	Grid Code / Technical Standard	Spinning Reserve / Inertia	Frequency Containment Reserve (FCR)	Limited Frequency Sensitive Mode – Overfrequency LFSM-O	Limited Frequency Sensitive Mode – Underfrequency LFSM-U
Germany - LV	VDE-AR-N 4105: 2018 [13]	Not available	Optional	Mandatory	Mandatory for BESS
Germany - MV	VDE-AR-N 4110: 2023 [14]	Not available	Optional	Mandatory	Mandatory
Austria	TOR Erzeuger -Typ A V1.2 [16]	Not required	Not required	Mandatory	Not required
Spain	NTS 631 V2: 2020 [18]	Not available	Optional	Mandatory	Mandatory for BESS
Italy	TIDE (Integrated Text on Electricity Dispatching) Italian Grid Code CEI 0-21 [17]	Ultra-Fast Reserve	Mandatory[1]	Mandatory	Mandatory
USA	IEEE Std 1547-2018 [19]	Not required	(Mandatory) due to very small deadband for LFSM-O/U	Mandatory	Mandatory
Australia	AS 4777-2:2020 [20]	Not available	Not required	Mandatory	Mandatory

Table 1 provides a short overview about IEA PVPS countries with frequency related grid code requirements for PV systems. Although Japan has also a remarkable penetration of PV power, frequency related requirements for grid connected PV systems are currently provided by the power market design and its regulations. A Japanese network code is planned to be stipulated LFSM-O/U response in 2025, which will cover PV systems as well.

3.2 Outlook

The latest developments with regard to the frequency related requirements for PV and PV BESS systems are based on the global targets for reduction of the GHG emissions and especially for the transition of the electric power supply. This power system transition is characterized by:

- Decommissioning of bulk power stations, which are equipped with rotating (synchronous) generators and fired by coal, other fossil fuels or nuclear energy and
- Strong increase of inverter coupled power stations from Renewable Energies Sources (RES), such as Wind Farms, PV Plants or Battery Energy Storage Systems (BESS).

Both trends have already led especially in power supply areas, with high share of Renewables to periods with inverter dominated power generation.

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[1] Mandatory for production units with power >= 10 MW (Italian Grid Code - Annex 15)

PV systems must be designed to provide primary frequency response in a manner similar to conventional rotating around the nominal frequency. This mode is called Frequency Sensitive Mode (FSM) must be activated upon request of the Manager in case of system needs (Annex 68 Italian Grid Code, CEI 0.21).

Power system stability studies from Transmission System Operators (TSO), their associations (entso-e) and power system regulators are coming also to the conclusion, that during the next years and decades the probability for the provision of pre-defined inertia constant is decreasing and the time periods with less than this inertia value are strongly increasing [4].

As it is depicted in Figure 3, a decrease of the inertia constant will lead to larger ROCOF values combined with a lower frequency nadir. Therefore, it is especially in low inertia or inverter dominated power systems necessary, that any active power imbalance would be reduced as soon as possible (e.g. within less than 5 s) by means of activating very fast active power reserves.

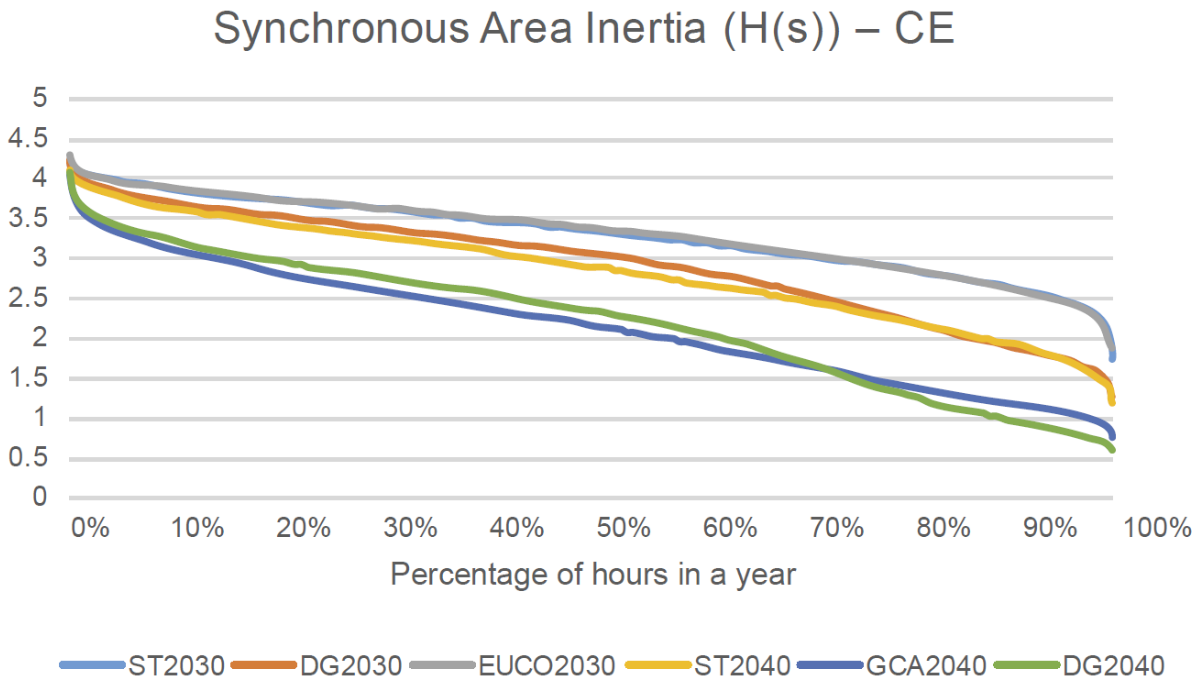


Figure 5: Duration curves of estimated equivalent inertia H(s) for the synchronous area of Continental Europe considering different power generation mixes [4]

As just explained, the spinning reserves of synchronous generating units and rotating loads depending on their intrinsic inertia are of high importance for power system stabilization. The emulation of a comparable behavior using the grid coupled power inverters of RES power stations is often called Synthetic inertia (SI). Synthetic Inertia is one of the most important capabilities of Grid Forming Inverters (GFI) and provides nearly instantaneously (within few cycles) active power proportional to the frequency gradient (ROCOF) value. In case of a frequency decrease (negative ROCOF value) the power generation of the GFI will be increased and if the frequency rises, the power generation will be reduced (according to the pre-defined Synthetic Inertia constant parameters.

The provision of Synthetic Inertia is currently not mandatory requested in Grid codes, but in the current draft of the of the lately revised European grid code Requirements for Generators (RfG) from 2023 [21] inverter coupled power stations (so called power park modules) of Type B, C and D must be able to contribute to Synthetic Inertia. The amount should be specified by the relevant system operator, where the power park module is connected to the public network.

Already nowadays the spinning reserves (kinetic energy) are sometimes very low in power systems, so that the activation times of Frequency Containment Reserves (FCR) are not fast enough to guarantee proper frequency stabilization esp. in case of severe power generation deficits (e.g. the reference incident).

The so-called Fast Frequency Response (FFR) was developed and implemented few years ago as a countermeasure to support a fast frequency recovery [22]. FFR is a variant of LFSM-O/U with much shorter activation times (approx. 1 s to 2 s) and thus contributes to very fast provision of missing active power. Inverter coupled power stations with grid following inverters are capable of providing this feature (FFR) and according to the latest draft of the European grid code Requirement for Generators (RfG) power park modules and Energy Storage Modules (ESM) of above 0.8 kW rated capacity are requested to contribute to this feature with very short response times (0 to 2s) [23].

4 OVERVIEW OF BEST PRACTISES AND FIELD EXPERIENCES

In this chapter an overview of best practices and field experiences in the context of frequency related services from PV systems will be provided. It shows various approaches and experiences in the different IEA PVPS member countries and thus helps to identify suitable frequency related services and its configurations for other countries.

4.1 Case study Austria – Synthetic inertia provision

Authors: Adolfo Anta, Peter Jonke, Roland Bründlinger (AIT)

Objective: Laboratory and field demonstration of the provision of synthetic inertia through storage systems
Field /laboratory configuration: 2x500 kW/500 kWh BESS connected to transmission substation
Used PV systems: -
Frequency service(s): Synthetic inertia
Applied inverter functions: Dynamic injection of active power, based on RoCoF
Main results: Validation of synthetic inertia provision of a MW scale inverter system through simulation, laboratory as well as field-tests. Investigation of various parameter settings related to their impact on stability, response dynamics and compatibility.

4.1.1 Synthetic inertia provision

To the best of our knowledge, most ongoing effort in demonstrating the capabilities of this function have focussed on using storage, rather than PV units. Nonetheless, the concepts are also valid for other inverter-based generation, provided that the energy source is able to vary as requested.

There are many definitions for synthetic inertia, which can be indeed a confusing term that has been employed to denote different inverter functionalities.

The main rationale behind this function is to mimic the behaviour of the inertial response of synchronous machines, where the active power is inversely proportional to the frequency gradient or rate-of-change-of-frequency (RoCoF).

In this case study, we focus on synthetic inertia implementations based on grid-following architectures, where the frequency is first measured (typically via a PLL), then RoCoF is computed, and then the power reference for the inverter is set according to a linear map, i.e., $P_{SI} = k_{SI}\frac{df}{dt}$.

The response of this function, that can be seen as a differential controller, is expected to be faster than standard frequency deviation, as it considers RoCoF values rather than waiting for the frequency to significantly deviate from the nominal frequency.

Nonlinear versions of synthetic inertia have also been proposed, including adaptive mechanisms for the synthetic inertia gain, or frequency and RoCoF dead bands. These are not particularly preferred by system operators as it complicates the system level analysis of this function.

Since this strategy relies on measuring the frequency first, for proper grid behaviour there needs to be another unit that defines the voltage magnitude and frequency, either a synchronous machine or a grid-forming unit. In that sense, synthetic inertia might contribute to system stability under moderate penetration levels of non-synchronous sources but does not enable a full transition towards 100% penetration.

Synthetic inertia is not a new concept, and Hydro-Québec was the first grid operator to mandate this capability in wind farms back in 2011. Nonetheless, its widespread implementation has been hampered by different factors, including lack of financial incentives, harmonized requirements, and some stability concerns.

Indeed, it has been conjectured [24] that, as the amount of synthetic inertia present in the grid increases, the function might create oscillations, mainly due to the inherent delay in the added feedback loop: frequency has to first be measured in a reliable way, the reference needs to be computed and the inverter has to track the new reference.

Similar strategies can be replicated using grid-forming architectures and are able to avoid this issue, although the technology is still in its infancy and there are many open unknows for grid-forming control, especially for its massive deployment in large grids.

4.1.2 Implementation of the concept

Given that synthetic inertia relies on computing a derivative, known to be very sensitive to noise, it is necessary to add filters in the RoCoF computation.

There is a clear trade-off between effectiveness, sensitivity and added delay. Existing grid code requirements do not define or suggest guidelines for proper filter design, since this also depends on the characteristics of the frequency measurement procedure, the amount of noise present in the measurements, etc.

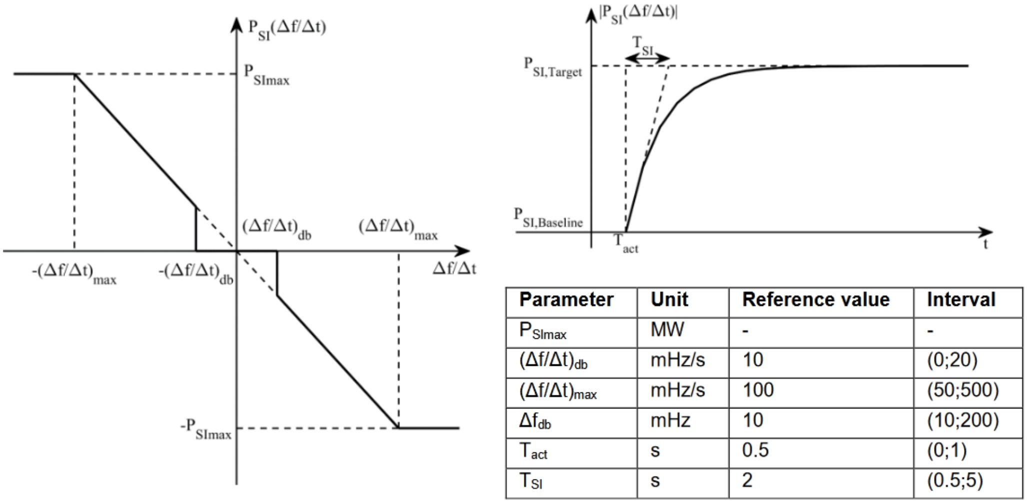
The function needs to be tuned in order to provide full support for frequency deviations with high RoCoF values and should be sensitive enough to respond as fast as possible, but at the same time should not be triggered by other grid events like oscillations or deterministic frequency deviations.

At the same time, during large RoCoF events the frequency gradient can be quite different across the grid, hence the expected response from this function cannot be uniform and will make the analysis more cumbersome, as aggregated models may not fully be accurate.

As in the case of frequency response, it is expected that adding frequency and RoCoF-dependent dead bands (and combinations thereof) helps in limiting the activation of this function to the relevant frequency excursions, excluding faults, deterministic frequency deviations, oscillations, etc. At the same time, such dead bands delay the response of SI, limiting its effectiveness. From all this, it is clear that the parametrization of this function is more convoluted than for frequency-based support services.

An extensive testing campaign might be required, that focusses on realistic frequency profiles rather than frequency steps or ramps (typically used for prequalification of frequency-based products).

Since SI only imitates the behaviour of synchronous generators, it is possible to alter its function to avoid unwanted effects, such as SI delaying frequency recovery after the frequency nadir. This can be achieved by implementing a zone-selective-control for SI and illustrated in Figure 7.



Parameter	Unit	Reference value	Interval
P_{SImax}	MW	-	-
$(\Delta f/\Delta t)_{db}$	mHz/s	10	(0;20)
$(\Delta f/\Delta t)_{max}$	mHz/s	100	(50;500)
Δf_{db}	mHz	10	(10;200)
T_{act}	s	0.5	(0;1)
T_{SI}	s	2	(0.5;5)

Figure 6: Frequency- and time-characteristic curves of SI [25]

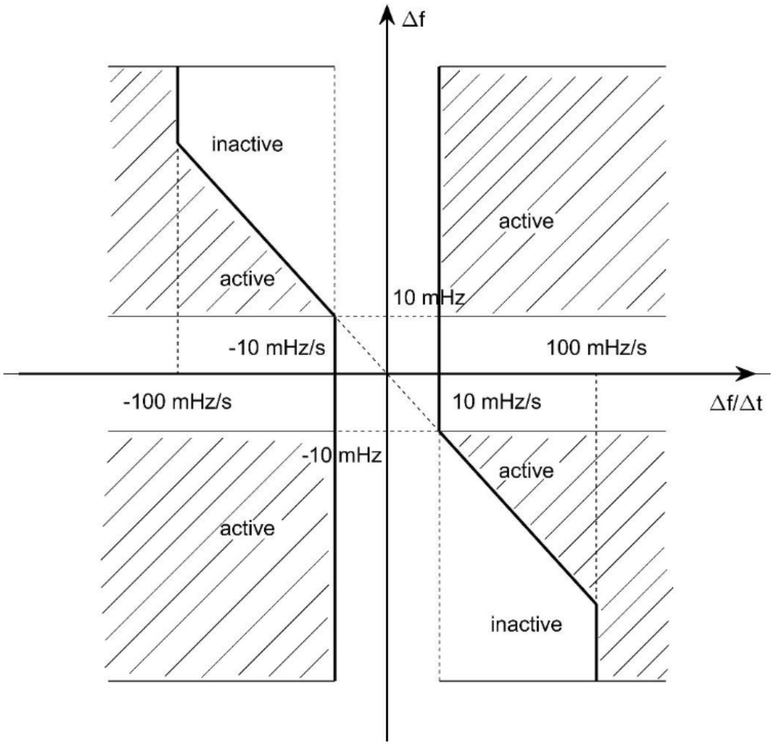


Figure 7: Zone-selective-control of SI [25]

4.1.3 Exemplary results

The above-described concepts have been implemented in the context of the ABS4TSO[2] project [25], with the help of a storage unit of 1MW/500kWh and two independent programmable inverters of 500 kW each.

It has been first tested in a controller Hardware-in-the-Loop environment, and afterwards in a lab setting with the help of a grid simulator, where different grid models and grid events can be replicated.

The first test consists of a standard frequency deviation profile from ENTSO-E, while the storage unit is providing enhanced frequency response (EFR) and synthetic inertia (SI).

Figure 8 shows the power provided by one of the inverters, where SI has a faster response and goes back to zero as the frequency approaches its Nadir.

Likewise, EFR ramps up slower than SI since it needs to first observe a significant frequency deviation but delivers a sustained response even after SI has disappeared. In that sense, the combined output of the two services EFR and SI provides an adequate response in this event.

As mentioned before, it is also important that the function does not react under other unrelated circumstances, for instance frequency oscillations where only power system stabilizers (PSS) should act.

Figure 9 shows the response to a historical recording of frequency oscillations in continental Europe. Of course, other types of settings (e.g., higher dead bands for RoCoF values or different filter parameters) might eliminate this undesired behaviour, at the cost of providing a worse response for high RoCoF events as in Figure 8. This highlights the convoluted trade-off for the parametrization needed in synthetic inertia.

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[2] ABS4TSO - Advanced Balancing Services for Transmission System Operators https://www.apg.at/projekte/abs-fuers-stromnetz/

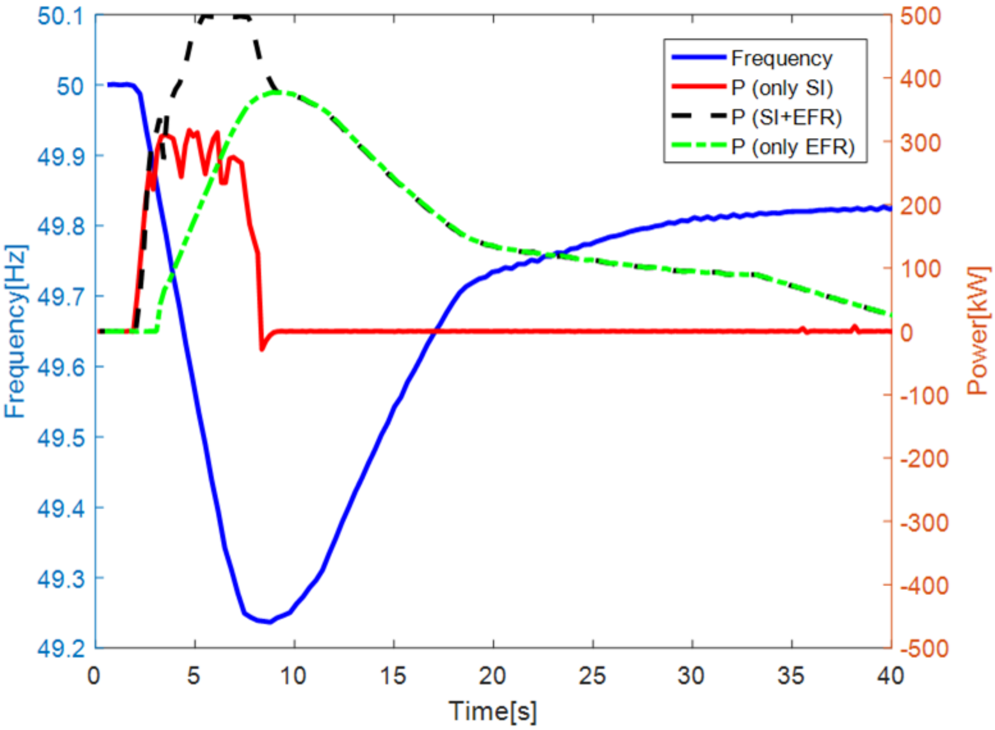


Figure 8: Multimodal operation (EFR + SI) to a standard frequency profile

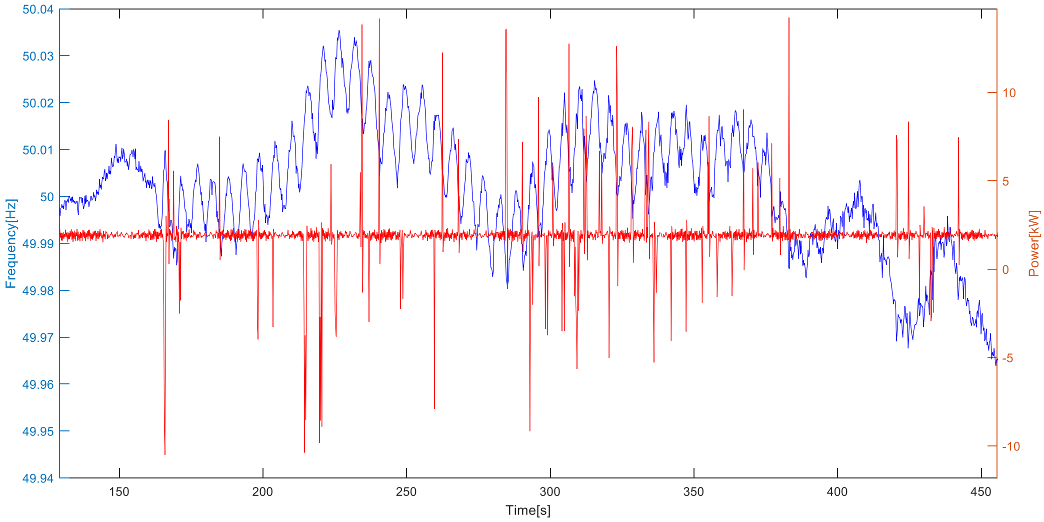


Figure 9: Storage response to oscillations in the grid

4.1.4 Recommendations and lessons learnt

The results of the project show that at some point, the further deployment of inverter-based resources will have significant impacts on the power system, most likely requiring technical countermeasures as well as adaptations to the regulatory framework.

As adaptations on the national as well as European regulatory level involve complex and long processes, it would therefore be beneficial to develop an implementation roadmap (see Figure 10), starting with measures that can be quickly implemented. In the next step, new ancillary services, operational principles are proposed. Eventually, considering scenarios with inverter dominated power systems, a paradigm shift towards grid-forming converter controls is expected.

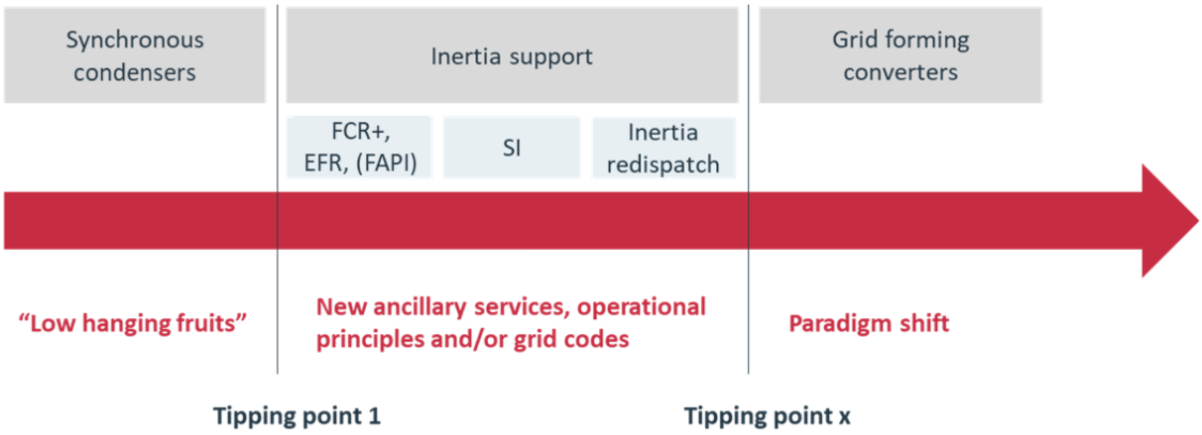


Figure 10: Exemplary implementation roadmap for frequency support services [25]

Phase 1 - Countermeasures, that can be quickly implemented: The rapid change of power systems and concerns over the loss of inertia have stimulated new interest in synchronous condensers, which mimic the operation of large conventional power plants by providing an alternative source of spinning inertia to stabilize the grid. A major advantage of these systems is that they are a very cost-effective and reliable way to maintain frequency stability in low inertia grids while they are also able to provide additional functionalities for TSOs (e.g. reactive power management or short circuit power).

Phase 2: New ancillary services, operational principles or inertia certificates basically have the highest suitability as future market products. An additional advantage of such future market products is that they could be also provided by existing units.

Furthermore, potential approaches of the fast control reserve concepts including SI can be found on EU-level as grid connection rules for the CE power system and used as potential starting points.

Phase 3: Paradigm shift – from grid-following to grid forming converters: Most inverter controllers today are grid-following and rely on a stable system voltage. Such control approaches do not inherently support the system and could potentially be the reason for potential frequency instabilities. This fact has given rise to the development of grid-forming control strategies for static converters, in order to enable inverter-based resources to deliver functionalities traditionally provided by rotating synchronous generation. The technical implementation of these capabilities as well as the establishment of appropriate specifications is currently in the focus of research and studies.

4.2 Case study Germany - Testing of frequency support features from Grid forming inverters

Authors: Gunter Arnold, Siddhi Shrikant Kulkarni, Nils Schäfer (Fraunhofer IEE)

Objective: Interaction of GFI with distributed PV systems and development of testing procedure for determination of synthetic inertia from GFI
Field /laboratory configuration: Indoor lab and outdoor test area in the test centre SysTec of Fraunhofer IEE
Used PV systems: Three rooftop PV systems in the outdoor test area and one GFI prototype
Frequency service(s): Spinning reserve, Frequency containment reserve (FCR), LFSM-O
Applied inverter functions: GFI: Synthetic Inertia response, primary frequency response, PV-Inverter: LFSM-O
Main results: Test procedures for spinning reserve of GFI and demonstration results of different frequency related services (Synthetic Inertia response/Spinning Reserve, Frequency Containment Reserves and Limited Frequency Sensitive Mode)

4.2.1 Objective

In the context of the German R&D project "Netzregelung 2.0" various lab tests as well as system tests were performed at the Fraunhofer IEE Test Center for Smart Grids and Electromobility (SysTec). The main objectives of these series of experiments are firstly to develop and validate test procedures for grid forming inverters (GFI) and secondly to analyse in a real distribution network environment the grid characteristics of GFI and the interactions between GFI, controllable loads and other Distributed Energy Resources (DER) such as PV systems, Battery energy storage systems (BESS), Windturbines (WT) and Diesel gen-sets [26].

In the course of the project "Netzregelung 2.0" especially test procedures as well as the following frequency related grid events and grid forming inverter functionalities had been investigated:

a) Development of test procedure for provision of synthetic inertia
b) (Transient) network frequency variations
    a. Frequency ramps with pos. & neg. ROCOF-values
c) Power sharing between different generating units
    a. Active power variation in case of over- and underfrequency (LFSM-O/U)

4.2.2 System configuration

Similar to the component tests it was also in the context of the system tests necessary to adapt and to configure the test setup based on the existing lab infrastructure of the SysTec according to the purpose of the investigations.

Figure 11 presents a simplified schematic of the lab infrastructure of the Fraunhofer IEE test center SysTec with the relevant grid components, generating units and programmable loads, which had been used for the system tests in various configurations.

The test center SysTec has a strong connection to the public medium voltage (MV) network and is internally equipped with different MV- and LV network segments, which allows various configurations. These different LV segments are supplied by one individually designed test transformer (T1) as well as by two standard distribution transformers (T2, T3). As generating units not only a 200 kVA rated Diesel-genset, a Windturbine (95 kW), three rooftop PV systems (7-9 kWp each), one battery energy storage system (60 kW rated power) but also one new GFI prototype (43 kVA) with hardware and software developed at Fraunhofer IEE are available for conducting the component and system tests. Furthermore, three fine-adjustable programmable RLC-load banks (two outdoor loads with 200 kW/100 kvar and the load bank inside the lab with 600 kW/ 600 kvar rated power) could be also utilized.

For investigations and tests regarding the operational behaviour in case of transient network frequency variations as well as during over- and underfrequency situations it is advisable to use a highly dynamic AC network simulator which offers the possibilities to change the setpoint online as well as the rate of change of the network frequency (ROCOF) in a wide range (e.g. nominal value ± 10%).

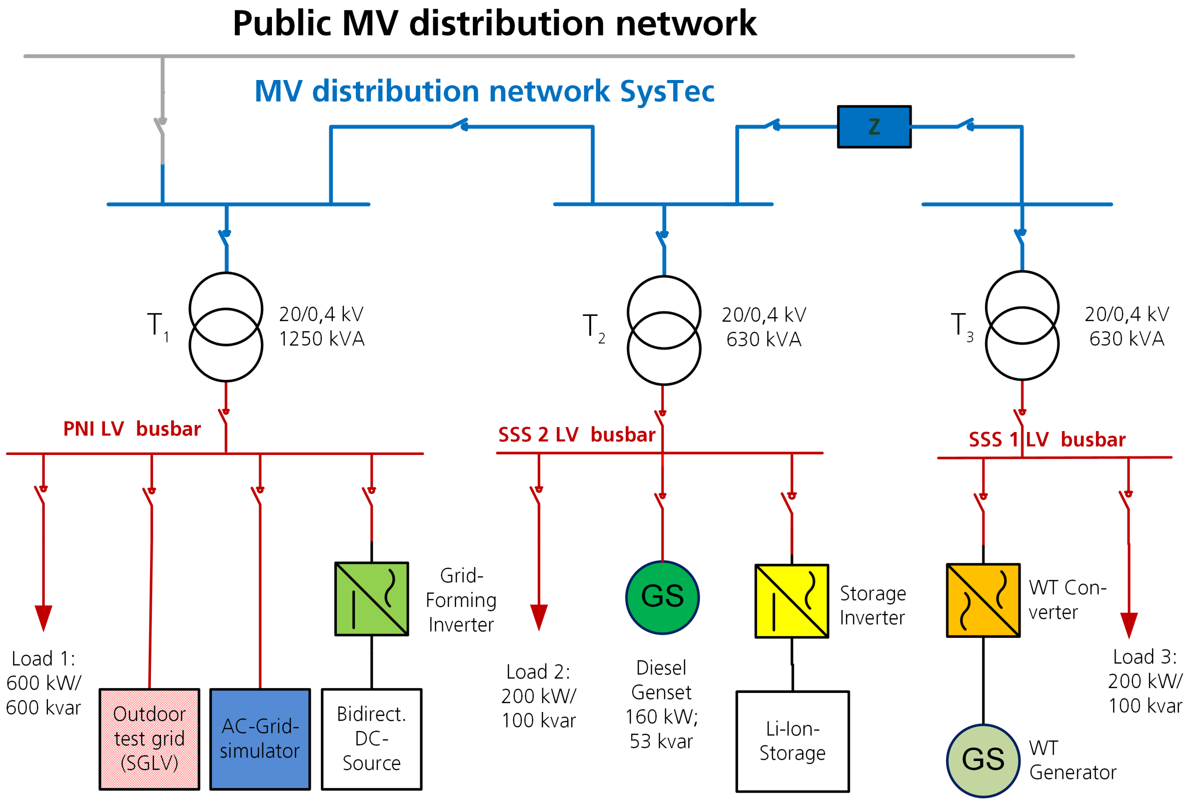


Figure 11: Simplified schematic of the lab infrastructure at the Fraunhofer IEE test center SysTec

4.2.3 Implemented frequency services and performed experiments

a) Development of test procedure for provision of synthetic inertia [27]

As part of the project work for the accurate characterisation of the synthetic inertia parameters of a GFI, the relation between frequency variations and inertia is exploited. One already well-established test procedure, the RoCoF test were adapted for the determining the inertia parameters and exemplarily results are presented here. The developed test methodology entails creating pre-defined linear frequency ramps (i.e. const. RoCoF values) in the grid and observing the Synthetic Inertia response from the GFI. The applied RoCoF testing sequences are based on the procedure described in EN 50549-10.

The tests are performed with a programmable LV AC grid simulator in order to manipulate the grid frequencies as necessary.

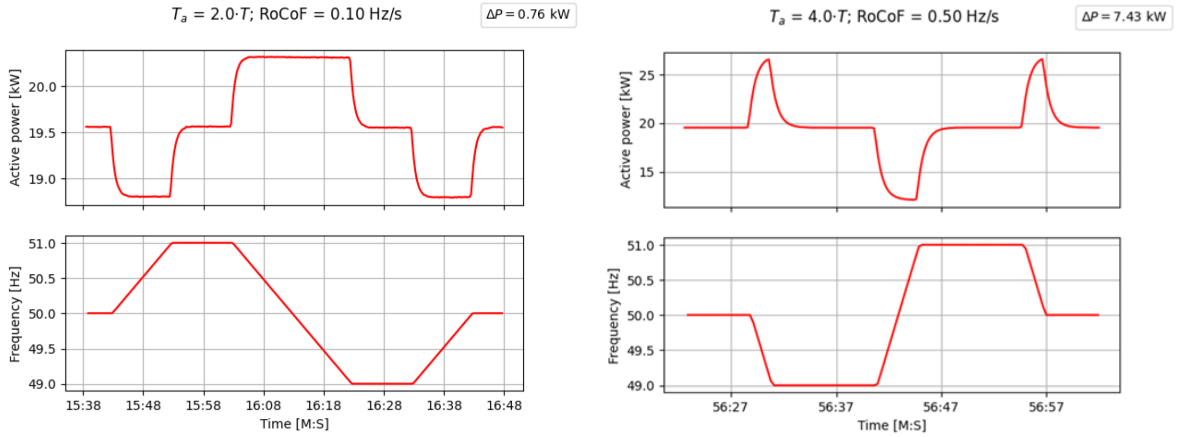


Figure 12: Active power output of the GFI and system frequency for a RoCoF test sequence with a) Ta = 2Ts and RoCoF = 0.10 Hz/s and b) Ta = 4Ts and RoCoF = 0.50 Hz/s [27]

Table 2 provides an overview of the results for the Synthetic Inertia response power ΔP from the GFI in the different RoCoF tests. For positive RoCoF values (increase of system frequency), the electrical power output of the GFI - similar to synchronous machines - is decreasing (negative ΔP) and vice versa for negative RoCoF values (decrease of system frequency) the Synthetic Inertia response power ΔP is positive. The provision of Synthetic Inertia response power for identical RoCoF values (except the sign) is symmetrical to the operating setpoint of the GFI.

Neglecting measurement and evaluation errors, then not only a linear relationship between the Synthetic Inertia response power and the acceleration time constant set value Ts, but also such a linear behaviour between ΔP and the applied RoCoF values can be observed.

Table 2: Overview of Synthetic Inertia response power ΔP for the GFI in the RoCoF tests [27]

Applied RoCoF [Hz/s]	ΔP [kW] Ts	ΔP [kW] 2Ts	ΔP [kW] 4Ts
0.10	-0.39	-0.76	-1.51
0.20	-0.77	-1.50	-2.99
0.33	-1.26	-2.49	-4.96
0.50	-1.89	-3.72	-7.41
-0.10	0.39	0.76	1.51
-0.20	0.77	1.51	3.00
-0.33	1.26	2.50	4.97
-0.50	1.89	3.73	7.43

b) (Transient) network frequency variations [26]

In the context of the system tests, several experiments with different configurations and parameter settings were conducted to investigate the behaviour in case of transient network frequency variations. Exemplary results regarding the operational behaviour of the system components and especially of the GFI in case of different frequency ramps will be presented here.

On August 3rd, 2022, experiments had been undertaken, in which not only the GFI in the testlab for grid integration (PNI) but also the three testhouses with their rooftop PV-systems in the outdoor test area Smart Grid Low Voltage (SGLV) participated. The complete test setup with the aforementioned generating units were supplied from the AC LV grid simulator, which allows to produce the network frequency variations depicted in Figure 13.

During these experiments, the GFI had been parametrised in such a way, that it not only provides synthetic inertia (SI) according to the frequency gradients but also contributes to Frequency Containment Reserve (FCR) in case of network frequency deviations from its nominal value of 50 Hz.

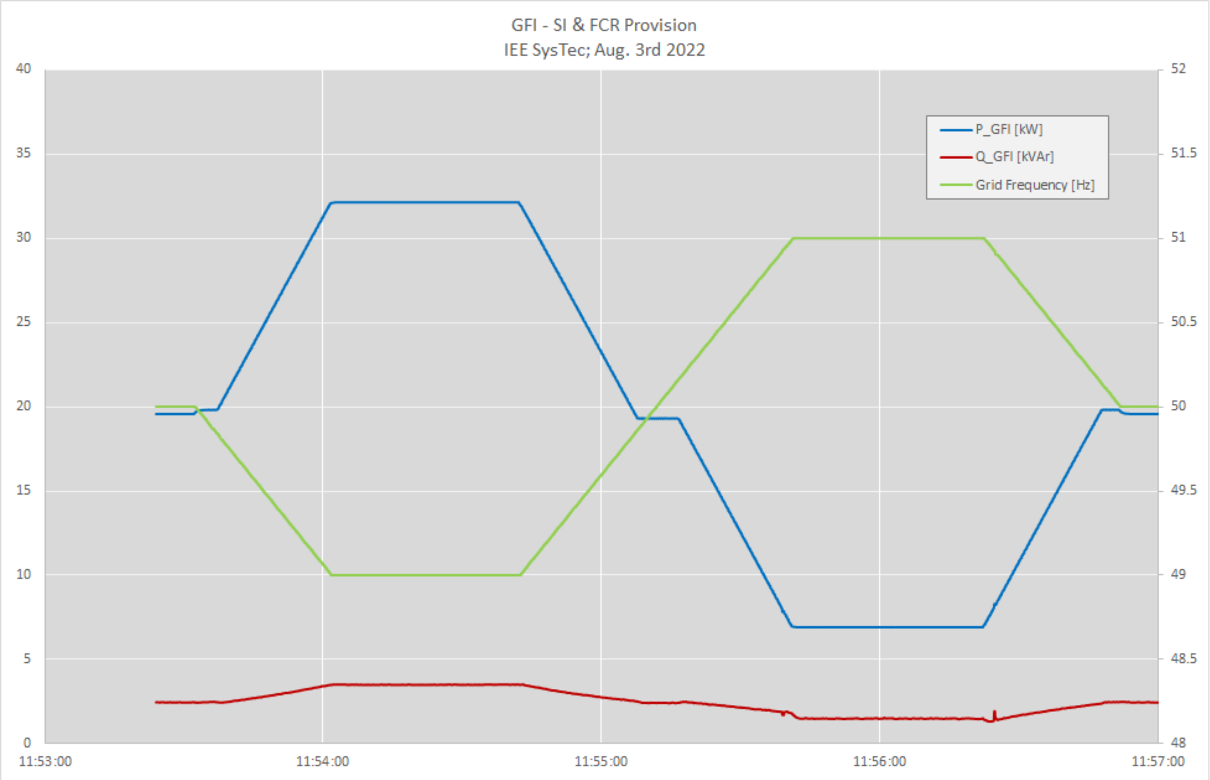


Figure 13: Provision of Synthetic Inertia response (Spinning Reserve) and Frequency Containment Reserve (P) as well as Reactive Power Q of the GFI in the PNI in case of rampwise network frequency variations

In Figure 13 Active Power P and Reactive Power Q of the GFI in the lab PNI are displayed for a sequence with ramp wise network frequency variations similar to the ROCOF tests for a time interval of 4 min.

During this period, the network frequency was at first decreased with a negative ROCOF-value of 0.033 Hz/s from its nominal value of 50.00 Hz down to 49.00 Hz. For the next 30 sec the network frequency was kept constant and subsequently it was increased with a positive ROCOF-value of 0.033 Hz/s from 49.00 Hz up to 51.00 Hz. Once again, for the next 30 sec it was kept constant and finally the network frequency was returned with a negative ROCOF-value of 0.033 Hz/s to its nominal value of 50.00 Hz.

With respect to the active power provision, a superposition of Synthetic Inertia response (Spinning Reserve) and Frequency Containment Reserve during this experiment is identifiable in Figure 13. The (positive and negative) contributions to Synthetic Inertia response (Spinning Reserve) occur during (negative and positive) frequency gradients, but with around ±0.250 kW they are much smaller compared to the Frequency Containment Reserve (±12.6 kW) in case of constant network frequency deviations of ± 1,0 Hz from its nominal value of 50 Hz.

c) Power sharing between different generation units, LFSM-O/U [26]

In the context of the system tests, several experiments with different configurations and parameter settings were conducted to investigate the behaviour in case of transient network frequency variations. Exemplary results regarding the operational behaviour of the system components and especially of the GFI in case of different frequency ramps are be presented here.

As already mentioned, on August 3rd, 2022, these experiments were undertaken, in which not only the GFI in the testing laboratory for grid integration (PNI) but also the three testhouses with their rooftop PV-systems in the outdoor test area SGLV participated. The complete test setup with the aforementioned generating units were supplied from the AC LV grid simulator, which allows to produce the network frequency variations as can be seen in Figure 14.

The PV inverters in the testhouses are pre-set according to the German LV grid code VDE-AR-N 4105.

During these experiments several overfrequency (51.0 Hz 51.2 Hz, 51.4 Hz etc.) and underfrequency setpoints had been tested using various ROCOF values.

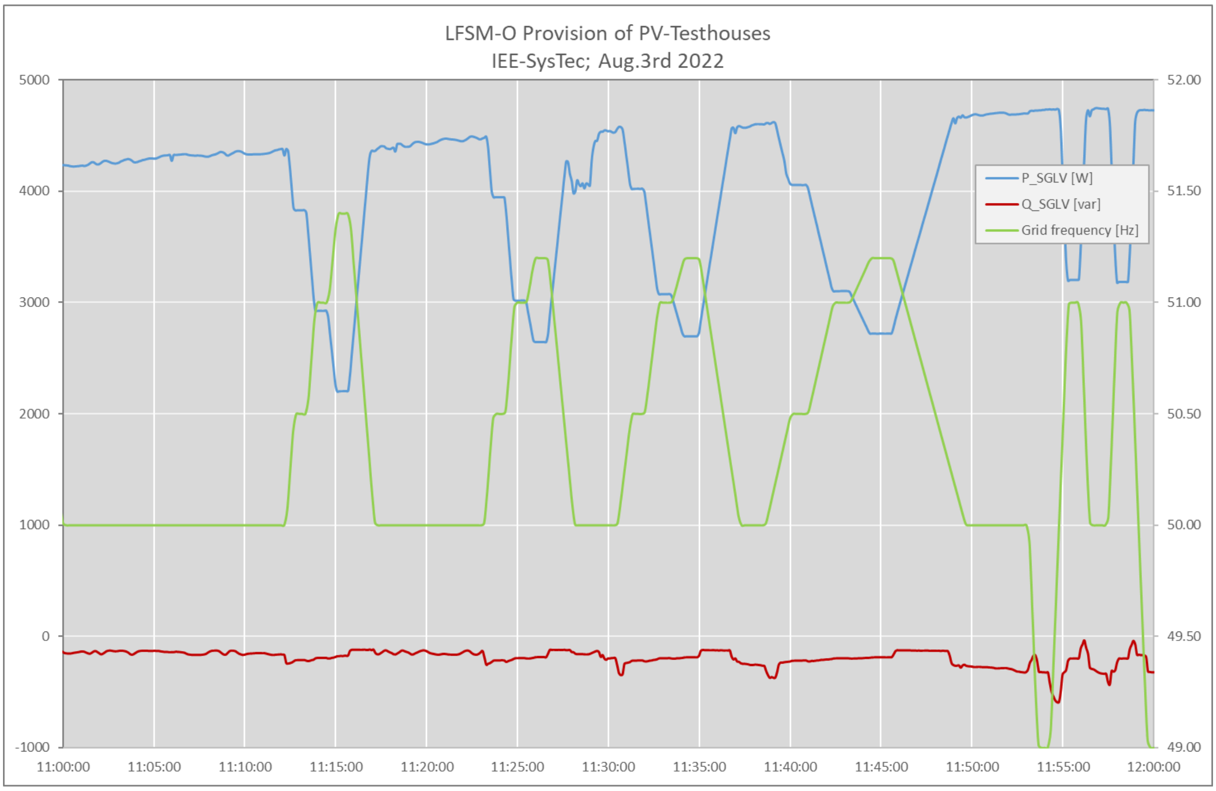


Figure 14: Power changes (Active Power P and Reactive Power Q of the outdoor test area (SGLV) in case of network frequency variations

Figure 14 shows an exemplarily network frequency course for a time interval of 60 min as well as the cumulative active and reactive power generation of the PV inverter in the outdoor test area on a sunny morning. Especially the active power generation mainly depends on the available DC-power of the solar PV panels according to the solar irradiation. Above the frequency threshold of 50.2 Hz the active power curtailment according to the LFSM-O characteristic (VDE-AR-N 4105) comes into effect. Thereto the active power generation of the PV systems in the outdoor test area, e.g. at a network frequency value of 51.2 Hz must be reduced by 40% compared to the available active power generation at 50.2 Hz.

In contrast to the PV systems, the GFI is contributing to Synthetic Inertia response (Spinning Reserve) and Frequency Containment Reserve (FCR) even during underfrequency situations, as it can be seen in Figure 13.

4.2.4 Main recommendations and key results

PV and PV-BESS systems equipped with grid forming inverters (GFI) offer the possibility to provide different frequency related services, such as frequency containment reserve (FCR) and Limited Frequency Sensitive Mode (LFSM-O/U) as well as an adaptable contribution to Synthetic Inertia response (Spinning Reserve).

In the context of German R&D project “Netzregelung 2.0” test procedures for determination of Spinning Reserve of grid forming inverters (using the ROCOF Test) and Frequency Containment reserve (FCR) had been developed and demonstrated. Especially for determination of the Synthetic Inertia response (Spinning Reserve) it is important to use frequency courses with adaptable constant ROCOF values. The ROCOF values should be selected in such a way that the operation limits of the Grid Forming inverters under test are not violated.

Furthermore, various systems tests had been undertaken during this project, which demonstrates the ability of Grid Forming Inverter in conjunction with distributed PV systems (Grid Following Inverter) to contribute to the different frequency related services such as Synthetic Inertia response (Spinning Reserve), FCR as well as LFSM-O.

4.3 Case study Italy - DC microgrid support for AC grid stability

Authors: Giovanna Adinolfi and Giorgio Graditi

Objective: DC microgrids supporting the main grid to mitigate frequency disturbances
Field /laboratory configuration: software implementation
Used PV systems: 800 kWp PV plant
Frequency service(s): Synthetic inertia, inertial response, power imbalance mitigation, tertiary reserve
Applied inverter functions: grid following, grid forming
Main results: DC resources can represent promising solutions to avoid power imbalances and to provide Synthetic Inertia, Inertial response, Ultra Rapid and manual Frequency Restoration Reserves (mFRR) to the AC grid in presence of massive RES integration and consuming units

Fit For 55 (FF55) package of EU Green New Deal prescribes 65% of renewable generation on the total electricity demand. The introduction of this large and intermittent production into the main AC grid and various sectors (mobility, cooling, heating, etc.) electrification can lead to frequency instability issues.

In fact, Variable Energy Resources (VERs) connection to AC grids are causing rotating masses generator decommissioning or functioning at minimum level during some hours of the day. With a limited presence of rotational inertia, these grids are not intrinsically able to face frequency deviations. This inability to oppose the change of frequency can determine grid stability criticalities affecting grid security. As reported in [30], in some years, PV plants will operate in curtailed mode for a significant number of hours during the year to reduce mentioned criticalities.

In literature different solutions to mimic rotational generators behaviour by Virtual Synchronous Generators (VSG), grid forming inverters and control logics are proposed. Most of them use storage as power sourcing/sinking systems to oppose overfrequency or underfrequency conditions.

Maximum attention is paid to this aspect by the regulatory authorities, normative bodies, and System Operators.

In fact, according to current normative (Comitato Elettrotecnico Italiano CEI 0-16 and CEI 0-21), compliant Medium Voltage (MV) and Low Voltage (LV) inverters must reduce/increase the active power input into the main grid (“LFSM-Overfrequency” function in Distributed Generation systems and “LFSM-Underfrequency” in case of Distributed Generation with storage systems) as countermeasures against frequency transient events.

In such context, it is underlining that PV and wind connection requests to the Italian High Voltage (HV), MV and LV lines reached 228 GW at the end of year 2022 (TSO data) which corresponds to 2.2 times the FF55 2030 objective (at least 102 GW by 2030).

The significant production of these RES plants will constitute a resource for the power system if

- a differentiation of their use is carried out;
- most of them can be controlled according to System Operator’s needs.

In this scenario, further solutions both habilitating the massive RES connection and mitigating/avoiding frequency (and security) criticalities to the main grid must be investigated.

Currently, numerous generators (PV, Fuel Cells, micro-wind, off-shore wind generators, etc), loads (lighting, cooling, mobility, etc) and storage (Li ion and H_2 based) are Direct Current (DC) native systems.

Research and industry are interested in the integration and management of these resources operating as a unique entity in DC grids and microgrids. In fact, they represent promising solutions able to work in islanded functioning mode or they can be connected to the main AC grid by inverter interfaces. At the moment, there are no standardized power or geographic limits for the maximum and minimum extent of a DC microgrid.

In this context, it is interesting to investigate the suitability of DC resources connected to HV, MV and LV lines to support the AC grid by a dual approach constituted by preventing and solving actions to face instabilities events.

The idea is to identify DC-native RES, also in aggregated systems with DC storage or DC loads, controlling them in zero AC grid feed-in mode, so reducing unwanted sourcing and sinking power flows to/from the main grid.

Such resources function in AC grid connected mode only in case of synthetic inertia, ancillary services or flexibility provision to system operators. Injection/absorption operations in/from the AC lines are agreed among the DC resources controllers and the system operators (Transmission System Operator and Distribution System Operator).

Since different DC-native RES generators with storage and consumption units (such as energy-intensive Data Centers) are interfaced to HV lines by converters, they could constitute “DC hubs”.

Equipping each DC hub with a synchronverter, it will be able to function as a Synthetic Inertia provider.

DC hubs could be generally operated in zero AC grid feed-in mode, but they could be connected to HV lines injecting or absorbing power mimicking synchronous generators behaviour.

A Day-Ahead inertia planning stage and a collaborative and coordinated scheduling strategy among the DC hub controller and the Transmission System Operator (TSO) can preventively act to mitigate frequency instabilities conditions, suitably managing DC resources and their functioning modes.

In addition, the synchronverter presence assures the hub ability to provide inertial response (solving action) in case of under/overfrequency disturbances in real time conditions.

On the other hand, DC-native resources connected to MV and LV distribution lines could constitute DC microgrids interfaced to the main AC grid by power electronic inverters.

Preventive actions are based on the idea of intentional zero AC grid feeding DC microgrids which embed renewable sources to optimally manage the variable production, also satisfying internal consumption and storage needs. Such DC microgrids allow to include significant renewable generation with not massive energy injection in the AC grid.

In the described scenario they could represent another compelling solution since they can pre-emptively act to mitigate energy surplus/deficit conditions, congestions, and load ramps [29].

In detail, these DC microgrids could be managed by TSO, under the Distribution System Operator (DSO) grant which has the Italian distribution lines visibility.

Preliminary data exchanges between the DC microgrid, the DSO and the TSO allow the DC microgrid controller to optimize internal resource matching the AC grid requirements and satisfying the internal load.

In agreement with the TSO, the DC microgrid absorbs energy from the main grid to reduce power imbalances when the AC grid risks overgeneration criticalities or when its consumption does not determine imbalances.

On the other side, the TSO is aware of the DC microgrid necessary absorbing or feeding power flows and it can adequately fulfill them by available grid resources.

It is underlining that the DSO grant is necessary to avoid TSO requests uncompliant with the distribution grid constraints.

The DC microgrid controller takes advantage of preliminary data exchange and uses it as constraints for the optimal management of DC resources.

In the following results obtained considering the power system in Figure 15 are reported.

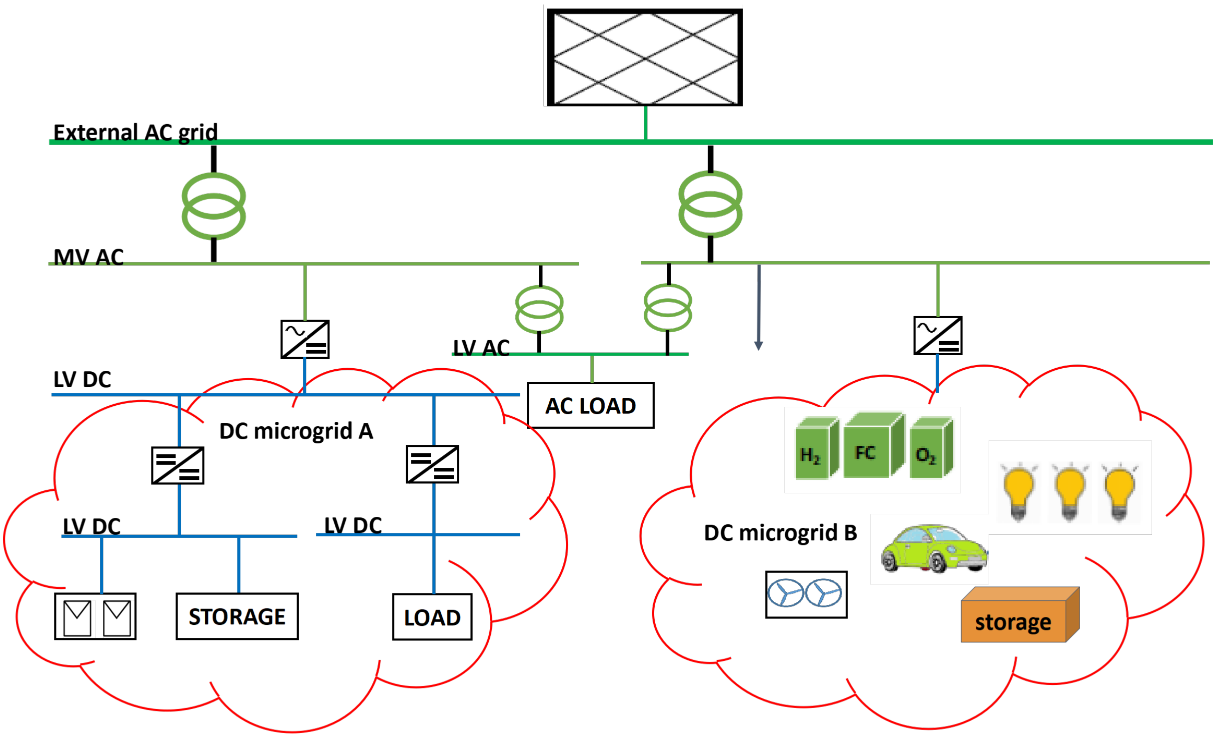


Figure 15: Use case power system

It is a radial AC grid characterized by the connection of AC loads and DC microgrids. The attention is focused on the DC microgrid "A". It is constituted by a PV-Battery Energy Storage System (BESS) plant and DC loads (generally represented with a unique load box in Figure 15 interfaced to the internal bus by DC/DC power electronics converters. It is characterized by an 800 kWp PV plant, 2.4 MWh storage systems and 300 kW DC-native loads.

A hierarchical control architecture is implemented: local controllers assure DC buses voltage stability while the DC microgrid controller executes the preventive optimized scheduling and runs it in the real time.

The proposed DC controller functions are developed taking advantage of Python Programming Language.

Considering PV production and demand forecasts relative to the D Day, the developed algorithm optimizes DC microgrid resources scheduling to fulfil internal needs also matching the TSO injection request. Such request is satisfied only when it is DSO granted. In case of TSO request uncompliant with DSO constraints, the DC microgrid controller optimizes the internal systems schedule maximizing self-consumption.

The obtained results are reported in the following figures.

In detail, Figure 16 reports the microgrid demand profile (E_DC_load - blue line) and Figure 17 shows the TSO requested profile (E_AC_req - sky blue line) to assure the power system balance.

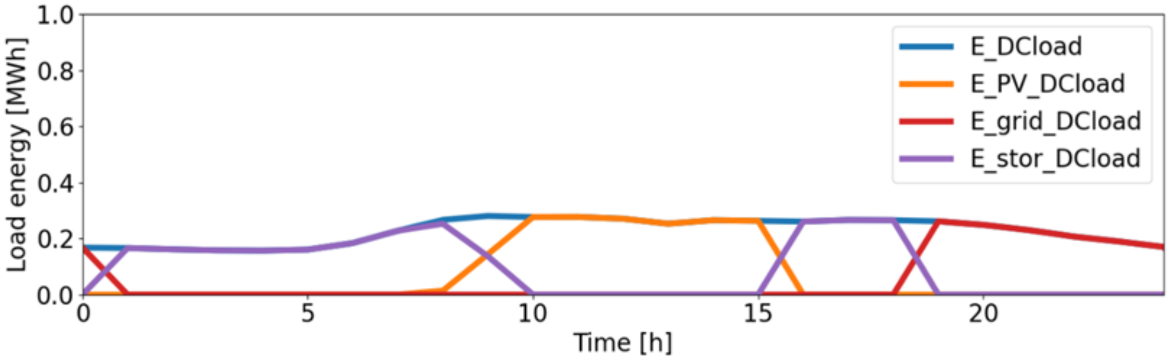


Figure 16: Energy profile corresponding to the DC microgrid load

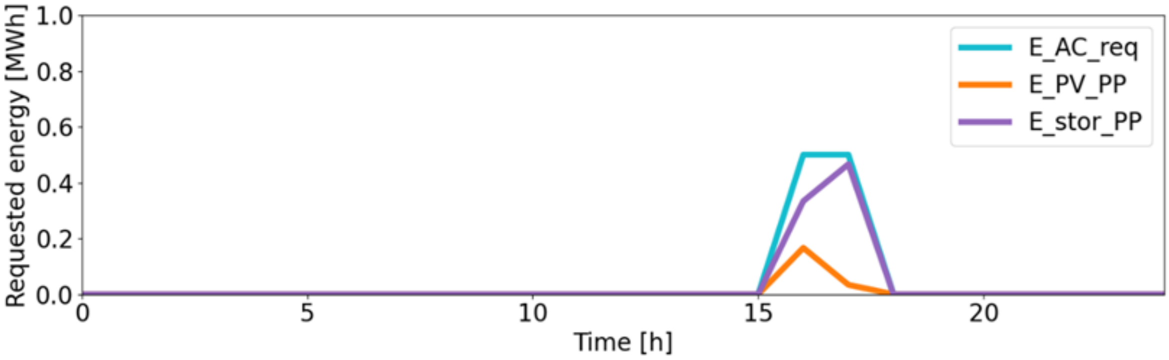


Figure 17: Energy profile corresponding to TSO (AC grid) request

As reported in Figure 16 the main grid feeds the microgrid load early in the morning and from 6 p.m. to 12 p.m.

Figure 18 reports the PV production graph. In particular, PV generation is employed to load fulfillment (E_PV_DCload) from 8 a.m. to 4 p.m. Surplus energy charges the storage system without affecting the AC grid. It is noting PV generation is not curtailed during the day.

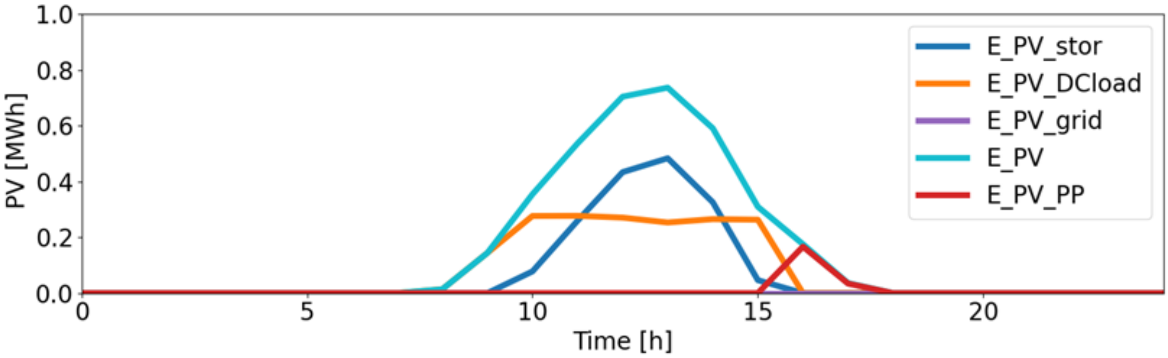


Figure 18: microgrid PV production

As shown in Figure 16, the storage system is involved in demand satisfaction until 10 a.m., then it is recharged by PV production from 9 a.m. to 3 p.m (Figure 18 and Figure 19). The AC grid feed the storage for a limited time interval (Figure 20). As reported in Figure 17, the storage (E_stor_PP – violet line) supports the AC grid in the interval 3 - 6 p.m. Also, PV production (E_PV_PP – orange line) contributes to energy provision to the main grid in the same time interval (Figure 17).

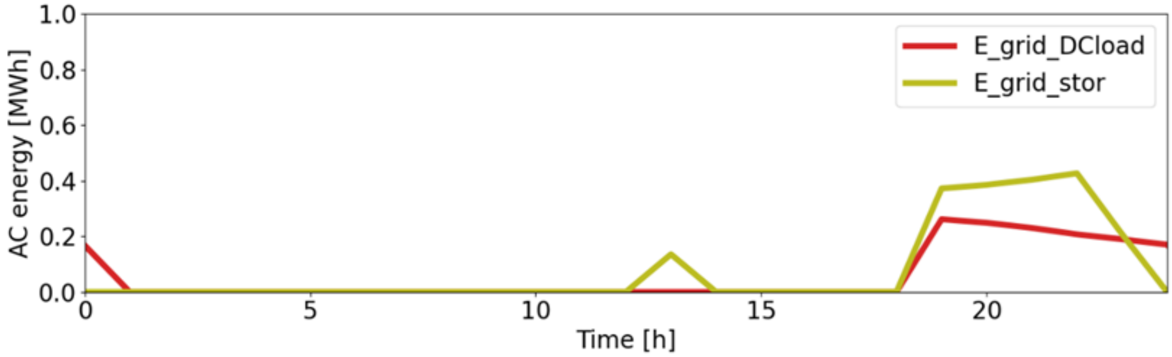


Figure 19: microgrid storage energy profile

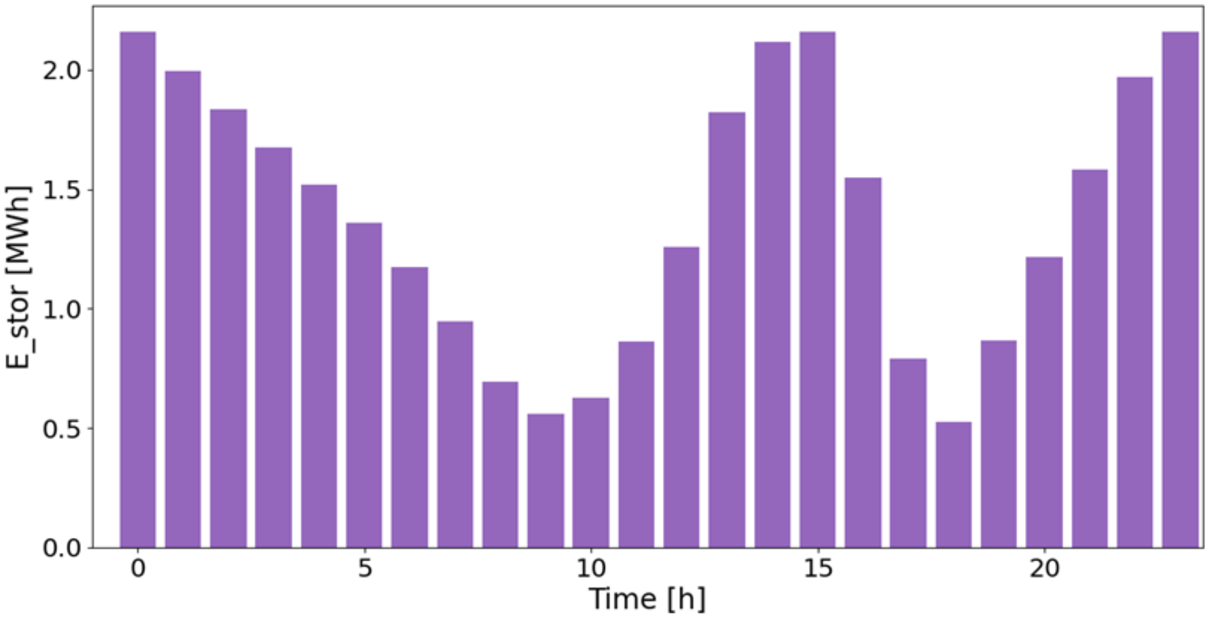


Figure 20: AC grid energy provision profile

The proposed method could be used to avoid/limit power imbalances due to RES injection and consuming units connected to MV and LV grids. Taking advantage of DC distribution different DC generators, load and storage systems can be managed without impacting the main AC grid with energy surplus/deficit conditions. Such solution reduces the losses due to every DC/AC conversion necessary in AC distribution with massive DC-native systems and equipment.

In real-time conditions (solving actions), DC microgrids could constitute prompt resources in case the main grid needs sourcing/sinking power flows to guarantee the power system stability.

Furthermore, DC microgrids can also work in grid-on mode (by inverters) to provide Manual Frequency Restoration Reserve (mFRR) to the main grid (solving actions). Figure 21 schematically represents the proposed strategy.

It starts during the day-ahead planning stage (D-1 Day) when TSO publishes hourly data about the necessary reserves during the D Day.

The DC microgrid controller analyses its renewable production and demand forecasts for the D Day. On this preliminary information, it runs an optimization algorithm to verify DC resource fitness to fulfill the internal load and to match TSO hourly profile.

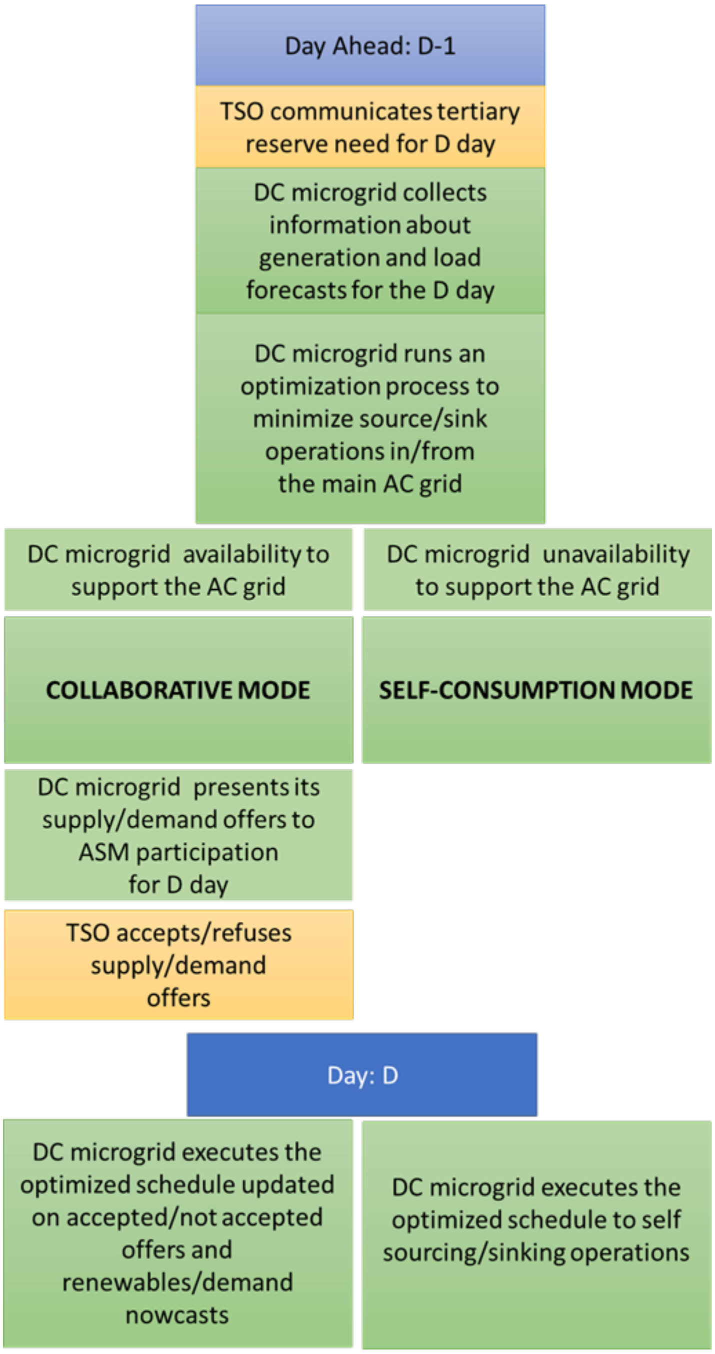


Figure 21: DC microgrid providing Manual Frequency Restoration Reserve (mFRR) to the main AC grid

In case the DC microgrid internal resources are sufficient to fulfil internal demand and to provide ancillary services to the AC grid, the controller communicates its availability to support the main grid according to the “collaborative mode”. Otherwise, it maximizes “self-consumption” operations.

In this case, the microgrid participates in the ASM for D Day energy provision. ASM accepted offers are remunerated at the pay-as-bid price and they outline the microgrid source/sink energy profiles during the D Day hours.

In real-time stage, the DC microgrid controller has to update the planned schedule considering the market accepted/not accepted offers and nowcast information by a rolling horizon optimization method to face RES and forecasting uncertainties.

Furthermore, the main grid can take advantage of microgrid resources in real time to promptly procure inertial response (Spinning Reserve) opposing frequency variations and RoCoF.

Main recommendations/lessons learnt

DC native resources (RES generators, load and storage systems) management in DC microgrids can represent a solution to carry out preventive and solving actions to mitigate/oppose grid frequency disturbances. The proposed solution is based on intentional zero AC grid feeding DC microgrids able to optimally manage internal resources to satisfy local consumption and to match TSO (planning and real-time) request. This optimization allows to reduce impacts due to significant renewable and consuming units' integration in the main grid, so mitigating frequency disturbances.

The presented case study reports results obtained with the collaborative functioning mode among the DC microgrid controller, the DSO and the TSO to provide and absorb agreed power flows. It is noting the collaborative management of DC microgrids could limit grid infrastructure reinforcement needs.

In addition, the provision of Inertial Response (Spinning Reserve) and Manual Frequency Restoration Reserve (mFRR) Reserve can be obtained by mentioned DC hubs and DC microgrids operating in grid-on mode by their electronic interfaces (synchronverters, inverters).

In the following table a schematic representation of DC hubs and DC microgrids support to the main AC grid is mapped:

Table 3: DC resources support to the main AC grid to mitigate frequency disturbances

Planning Stage		**Real time Stage**	
Preventive Actions	**Solving Actions**	**Preventive Actions**	**Solving Actions**
HV: DC hubs + synchronverters: Synthetic Inertia provision		HV: DC hubs + synchronverters: Inertial response provision	Spinning Reserve use
MV, LV: DC microgrids + inverters: scheduling optimization to avoid power surplus/deficit conditions	Manual Frequency Restoration Reserve (mFRR) planning	MV, LV: DC microgrids + inverters: scheduling optimization to face forecasting uncertainties	Manual Frequency Restoration Reserve (mFRR) use

4.4 Case study Japan – Provision of inertia

Authors: Yuzuru Ueda (Tokyo University of Science), Yuka Ogasawara (NEDO), Eitaro Omine (NEDO)

Contributors: Hiroshi Kikusato, Dai Orihara, Jun Hashimoto (National Institute of Advanced Industrial Science and Technology (AIST)

Objective: Evaluation of inverters with implement functions including synthetic-inertia to accommodate future low-inertia
Field /laboratory configuration: EMT simulation, PHIL tests, etc.
Used PV systems: -
Frequency service(s): Synthetic inertia
Applied inverter functions: df/dt-P droop, f-P droop, VSM, Q-V droop
Main results: Key performed experiments on frequency support by PHIL tests for inverter based DERs with synthetic inertia, considering not only for BESS but also for PV and WT

4.4.1 Objective

In anticipation of decarbonization of electricity, the Japanese government announced the goal of the renewable energy ratio of around 36-38% (336-353TWh) by 2030, in October of 2021. The ratio of photovoltaic (PV) and wind turbine (WT) power generation would be accounted for about 14-16% (131-149 TWh, 103.5-117.6 GW) and 5% (47 TWh, onshore 17.9 GW and offshore 5.7 GW), which are inverter-based DER (IBR). The increase in inverter-based DER may reduce the number of synchronous generators such as thermal power generation connected to the power grid, and they decrease the overall inertia and synchronizing power as well as short-circuit capacity of the grid.

To mitigate these problems, NEDO has been focused on addressing both technical and institutional challenges in the future power grids at the “Future-generation power network Stabilization Technology development for utilization of Renewable Energy as the Major power source (STREAM)” project from 2022 [30]. Especially, NEDO promotes development of inverters with synthetic inertia, not only for BESS but also for PV and WT. During the daytime or at night, when residual demand is low, RE curtailment is performed more frequently based on commands from TSO/DSO, not LFSM-O/U response, so PV or WT without BESS can provide instantaneously active power proportional to a frequency gradient value, according to the curtailed amount [31].The developed technologies will be tested in a small-scale grid to verify their effectiveness and data will be acquired necessary for reflection in the Japanese grid codes.

Before the STREAM project, from 2019 to 2021, NEDO conducted the project titled "Next-Generation Power Network Stabilization Technology Development for Large-Scale Integration of Renewable Energies" [32]. In this project, defined the functions of the grid forming inverter that implements functions including synthetic-inertia to accommodate future low-inertia grids, and prototypes were developed with appropriate functions. As well as the electromagnetic transient (EMT) simulation of the prototype, the application effects of the grid forming inverter were also verified through actual equipment tests using the power hardware-in-the-loop (PHIL) technique by the AIST and the Tokyo Electric Power Company Holdings, Inc.. As the result of these tests, the issues that need to be solved by the STREAM project had clarified. The outline of PHIL tests and extracted issues by the existing Japanese conformance test is shown below.

4.4.2 PHIL tests configuration

First, in this project, synthetic inertial control algorithms were classified [33]. The classification focuses on the operational capabilities of power supplies equipped with control algorithms and is divided into Grid-Forming types (henceforth, GFM), which behave as voltage sources and Grid-Following types (henceforth, GFL), which behave as current sources. Then, the inverter prototypes were tested under the selected test cases by PHIL technique, after the EMT simulation to determine key performance indicators (KPIs) and test cases [34] [35].

The inverter prototypes were four BESS inverters with advanced control functions from different manufacturers, shown in Table 4. Although BESS inverters were used, differences in the backing power supply were not considered in these tests. The prototype1 has both GFL and GFM characteristics, which can only enable either.

Table 4: Specifications of inverter prototypes [34]

Name and inverter types	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
Rated capacity	20 kVA	49.9 kVA	12 kVA	20 kVA	50 kVA
Advanced control functions	df/dt-P droop, f-P droop	df/dt-P droop, f-P droop	VSM, Q-V droop	P-f droop, Q-V droop	VSM, Q-V droop
IDM (reactive method; active method)	Voltage phase angle jump detection; Frequency feedback method with step reactive power injection	RoCoF change detection; Frequency shift method	Unimplemented	Voltage phase angle jump detection; Frequency feedback method with step reactive power injection	Voltage phase angle jump detection; Frequency feedback method with step reactive power injection
Prototype number	Prototype 1	Prototype 2	Prototype 3	Prototype 1	Prototype 4

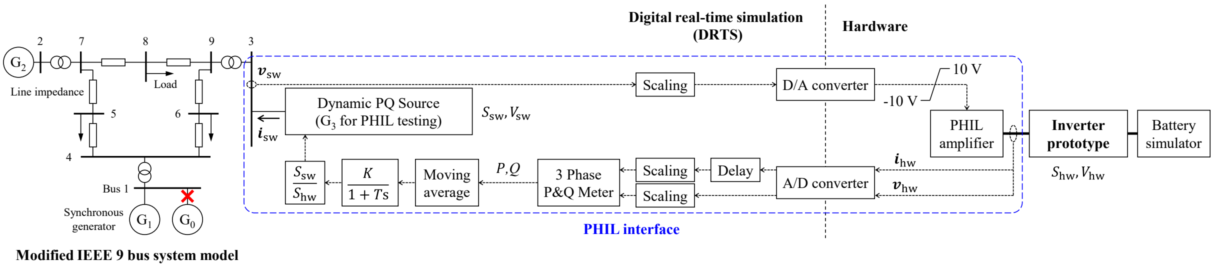
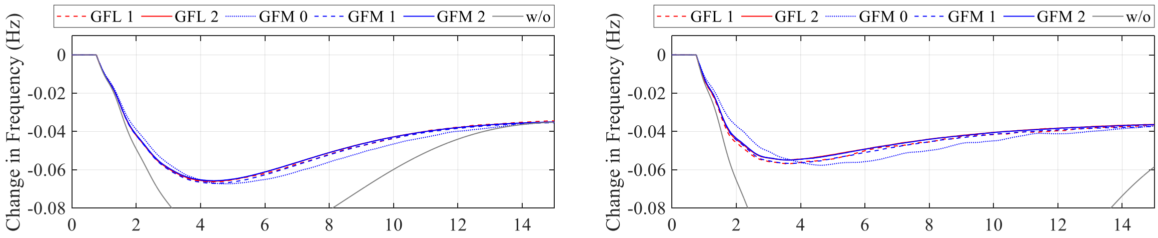


Figure 22: Configuration of PHIL testing [34]

In the PHIL tests, a power grid was modelled in the digital real-time simulation (DRTS) based on the IEEE 9-bus system model [38], and each inverter prototype was connected equivalently to the synchronous generator (SG), G3 under the bus 3 via the PHIL interface shown in Figure 22. The total generator capacity of G1 to G3 was 300 MVA; the G3 ratio (henceforth, Inverter-based DER (IBR) ratio) was set to 20, 40, 60, and 80%, and the remaining capacity was divided equally between G1 and G2. The load factors of L1 to L3 were set to 40%, and their capacities were equal. The SG of G0 (generator capacity 10 MVA, active power output 5 MW) was assumed to trip, resulting in frequency change.

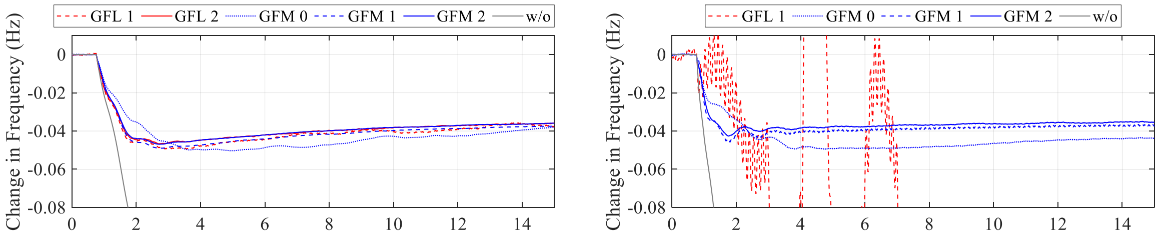
4.4.3 Key performed experiments on frequency support by PHIL tests

Figure 23 shows the change in grid frequency after generation trip under conditions where the inverter-based DER (IBR) ratio is 20, 40, 60, and 80%, respectively. The generator trip occurred at 0.75s. Focusing on conventional inverter (w/o), it can be seen as the IBR ratio increases, the reduction in system frequency increases. On the other hand, both GFL and GFM with advanced control functions suppresses the drop in system frequency after generation trip, when the IBR ratio is 20 to 60%, and the effectiveness of the advanced control functions suppresses can be confirmed. Furthermore, if the IBR ratio is 80%, it can be seen it was able to operate stably in GFM while the grid became unstable in GFL. These results suggest that GFM would become one of contributing solutions if the IBR ratio increases significantly.



(a) IBR ratio 20%

(b) IBR ratio 40%



(c) IBR ratio 60%

(d) IBR ratio 80%

Figure 23: Frequency change after generation trip [34]

4.4.4 Extracted issues by Japanese conformance tests

In Japan, to omit individual performance confirmation tests, etc. in interconnection discussions between TSO/DSO companies and power generation installers, there is the optional certification system for inverter-based DER products interconnecting in distribution grids to comply with the standards by the Japan Electrical Safety & Environment Technology Laboratories (JET) based on the Grid Interconnection Technical Requirements Guidelines, Electrical Appliance and Material Safety Act, etc.

In this project, the existing Japanese conformance testing was also applied to the inverter prototypes [37]. The tests were conducted evaluating change in grid voltage and frequency and phase-angle, and the results are shown in Table 5.

Table 5: Result of existing Japanese conformance test for each inverter prototype [37]

#	Test	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
1	Test for over/under-voltage trip	C*	C	N	N	N
2	Test for over/under-frequency trip	C*	C	N	N	N
3	Unintentional islanding test	C*	C*	-	N	C*
4	Test for voltage magnitude change within continuous operation region	C	C	N	C	C
5	Test for voltage phase angle change	C	C	C	N	N
6	Test for low/high-voltage ride-through	C*	C*	N	N	N
7	Test for low/high-frequency ride-through	C	C	N	N	C

C: Conformance; N: Non-conformance; -: Not conducted

* Conformance can be expected by making minor corrections to device configuration, control logic, and more

The test results showed that the GFL inverters were conforming in all tests conducted, while the GFM inverters were non-conforming in most tests. Additionally, three issues were identified in the GFM inverters: i) unwanted tripping by OCR due to change in grid voltage, ii) active power swing after recovery from a voltage sag, and iii) coexistence of grid stabilization capability and islanding detection. Based on these test results and knowledge, NEDO has started the STREAM project to conduct R&D which make it helpful for discussing future provisions on the technical requirements of inverters and their verification methods.

4.5 Case study Japan – Headroom control

Authors: Takashi Oozeki (National Institute of Advanced Industrial Science and Technology (AIST), Yuzuru Ueda (Tokyo University of Science)

Contributors: Takahiro Takamatsu, Hideaki Ohtake, Jun Hashimoto, Kenji Otani (National Institute of Advanced Industrial Science and Technology (AIST), Jindan Cui (Tokyo University of Science)

Objective: A method of creating upward flexibility by means of the headroom control

Field /laboratory configuration: Field

Used PV systems: 250 kW

Frequency service(s): Provision of upward reserve

Applied inverter functions:

Main results: The experimental results of headroom control indicated the possibility to provide the upward flexibility from PV

4.5.1 Objective

As the amount of installed PV increases, the kWh value of PV during daytime hours is expected to decline. In order to sustain the PV power generation business in such a circumstance, it is necessary to improve the value and flexibility of PV as a power source. This study aims to demonstrate the effectiveness of headroom control technologies to provide the upward flexibility of PV. The headroom control method intentionally reduces output to a certain degree and then increases output when it is requested. Some studies have used the headroom for auto governor control and frequency-watt (LFSM O/U) in their 300 MW systems.[38] Since PV output has fluctuations due to weather changes, it is important to determine the appropriate range of output reduction. One of the methods is to estimate the PV power output corresponding to the irradiance in real time, and then reduce the commanded percentage of output to ensure the capability of upside power output. We have studied headroom control as flexibility from PV in real system.

4.5.2 Method, Experiment

The experiment was conducted using a 250kW DC/250kW AC system installed at the Fukushima Renewable Energy Research Institute of the National Institute of Advanced Industrial Science and Technology. An irradiance data collection device using a solar cell pyranometer, a device that uses irradiance data to estimate expected PV output power, and a inverter that can be controlled by the headroom ratio (ΔP) secured to the expected generated power were installed in a PV system (see Figure 24). The irradiance intensity is measured at five locations. A simple polynomial was used to estimate expected PV output power from irradiance. From Aug. 19, 2022 to Aug. 22 from 10:00 to 15:00, we conducted an experiment with Headroom control for the first 30 minutes and full power for the second 30 minutes in every hour. The amount of headroom that is expected to be secured for each time period is as follows; 10:00-10:30: 25 kW, 11:00-11:30: 50 kW, 12:00-12:30: 75 kW, 13:00-13:30: 50 kW,14:00-14:30: 25 kW.

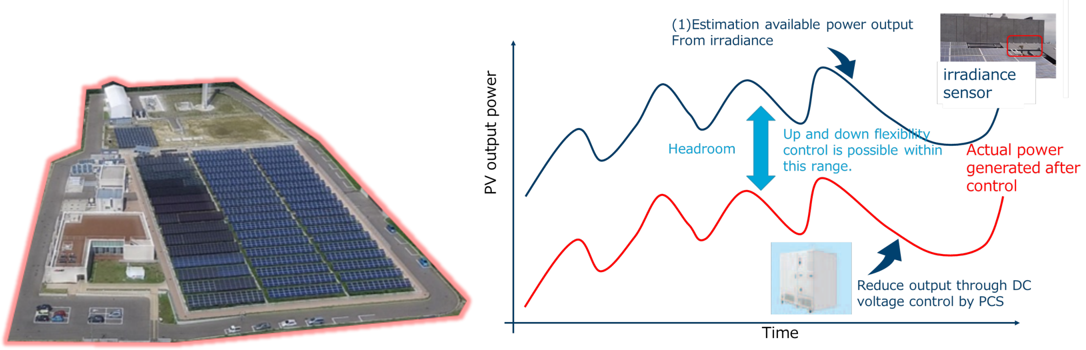
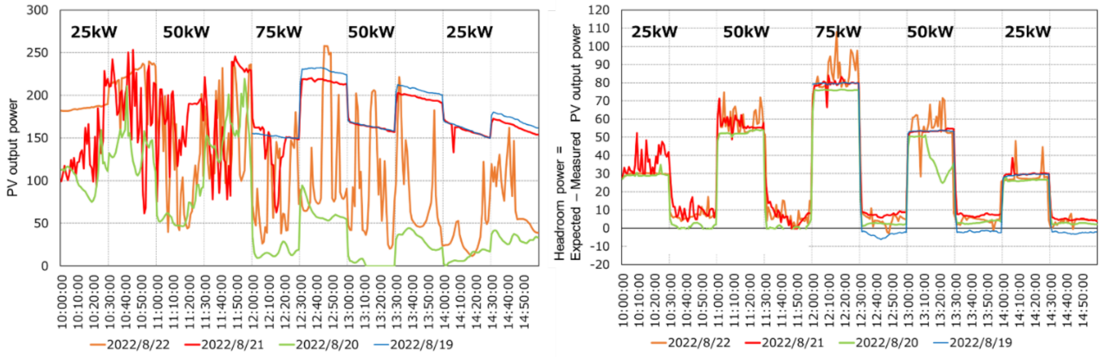


Figure 24: Schematic diagram of PV headroom control (250kW)

4.5.3 Results

Measured data of PV output power in demonstration experiment was shown in Figure 25(a). Estimated amount of headroom power, the difference between the estimated expected PV output power and the actually measured PV output power, was also shown in Figure 25(b). PV system was able to have headroom power stably on August 19th as clear day condition, but headroom power can also fluctuate on the days with a lot of fluctuations on August 21st. In addition, there were cases such as 13:00 on August 20th when PV system could not have headroom power as expected due to cloudy weather.



(a) Measured PV output power (b) an estimate of the amount of headroom power

Figure 25: An example result of PV headroom control

4.5.4 Recommendations and lessons learnt

The experimental results of headroom control indicated the possibility to provide the upward flexibility from PV in the power grid. In the future, it will be necessary to develop accurate estimation and control methods of headroom, planning strategies using headroom power, and energy and design of balancing market to utilize the flexibility of PV systems.

5 KEY FINDINGS AND RECOMMENDATIONS

This report describes the mechanisms of frequency control in AC power systems through balancing active power generation and demand. It is focussed on frequency related services from distributed PV and BESS systems and provides an overview about the results of selected R&D projects from different IEA member states.

The projects have clearly demonstrated that PV Systems solely or esp. in combination with BESS are able to provide different types of frequency related grid services.

Since several years PV systems equipped with grid following PV inverters must contribute to certain services such as the reduction of active power generation in case of overfrequency situations (LFSM-O).

In combination with Battery Electric Storage Systems (BESS) they are also often requested to increase their active power output if an underfrequency event occurs (LFSM-U).

Furthermore, it can be stated that the LFSM-O/U response times of PV inverters and the BESS systems are remarkable shorter compared to rotating generating units such as steam plants or CHP units. This short response times allows PV and BESS systems in principle to contribute to Fast Frequency Response (FFR).

The intrinsic inertia of synchronous generating units and rotating loads is of high importance for frequency stabilisation in power systems. The emulation of a comparable behaviour using the grid coupled power inverters of RES power stations is often called Synthetic Inertia (SI). This is one of the most important capabilities of Grid Forming Inverters (GFI) and provides nearly instantaneously (within a few cycles) active power proportional to a frequency gradient (ROCOF) value.

The provision of such very fast frequency services by PV systems (with or without batteries) will become very important in near future, especially in supply areas which are dominated by inverter coupled generators.

Clearly and precisely stipulated requirements as well as standardized or at least harmonized testing procedures are a key for compliance assessment of different PV systems and for comparison of its contributions to frequency related services.

Fast frequency services by PV systems using grid following inverters are currently either a mandatory requirement for large PV Plants connected to HV or EHV networks or on the other hand could be offered optional on power balancing markets (depending on power market design).

A similar approach (grid code requirement and participation on the power balancing market) would be also suitable for the introduction and implementation of the very fast frequency services of grid forming inverters (GFI) such as Synthetic Inertia (SI) provision.

Concluding it can be said that the results of the described case studies are promising, but further research and demonstration projects are necessary esp. for implementation of these frequency related services, which come along with Grid Forming Inverters (GFI).

6 SUMMARY AND OUTLOOK

Solar PV and Windenergy in combination with dispatchable RES are becoming globally the most important energy sources in the future electricity supply. Thus, solar PV systems as well as other inverter coupled generators and storage units must take over additional grid supporting tasks of conventional power plants in order to allow for secure and stable operation of electrical power systems at all times.

This report aims to present the status and the potential of distributed solar PV and PV hybrid systems with respect to provision of frequency related services. Subsequent to an introduction of the various measures in the context of frequency control, it provides an overview of corresponding grid code requirements. The main chapter of this report contains a collection of uses cases (field experiences and laboratory results) from different IEA PVPS countries. The target groups of this publication are especially grid operators and decision-makers, which may not be aware of the state of the art and the potential of PV and PV hybrids system with respect to provision of frequency related services. The main focus of this report is to give an overview in the context of frequency related services and to introduce exemplarily good practices from different IEA PVPS member countries.

The results of the Austrian project show that at some point, the further deployment of inverter-based resources will have significant impacts on the power system, most likely requiring technical countermeasures as well as adaptations to the regulatory framework.

As adaptations on the national as well as European regulatory level involve complex and long processes, it would therefore be beneficial to develop an implementation roadmap with three steps: Starting with countermeasures for power system stabilisation, that can be quickly implemented such as synchronous condensers. In the next step, new ancillary services, operational principles are proposed. In step 3 scenarios with inverter dominated power systems are considered and a paradigm shift towards grid-forming converter controls is expected. The technical implementation of these capabilities as well as the establishment of appropriate specifications is currently in the focus of research and studies.

In the context of the German research project “Netzregelung 2.0” (Grid Control 2.0) test procedures for determination of Synthetic Inertia response (Spinning Reserve) of Grid Forming inverters (using the ROCOF Test) and Frequency Containment reserve (FCR) had been developed and demonstrated at the Fraunhofer IEE test centre SysTec. Especially for determination of the Spinning Reserve contribution it is important to use frequency courses with adaptable constant ROCOF values. The ROCOF values should be selected in such a way that the operation limits of the Grid Forming inverters under test are not violated.

Furthermore, various systems tests had been undertaken during this project, which demonstrates the ability of Grid Forming Inverter in conjunction with distributed PV systems (Grid Following Inverter) to contribute to the different frequency related services such as Synthetic Inertia response (Spinning Reserve), FCR as well as LFSM-O.

An Italian research activity investigates DC microgrids contribution to support the main AC grid to prevent and oppose frequency disturbances. The proposed solution is based on intentional islanded DC microgrids able to optimally manage internal resources to satisfy local consumption and to match TSO (planning and real-time) request in terms of sourcing/sinking power flows via inverter interfaces. This optimization allows to reduce impacts due to significant renewable and consuming units’ integration in the main grid, so mitigating over/underfrequency conditions.

In the frame of the Japanese research project STREAM, PHIL based investigations for the provision of ancillary services by different inverter prototypes with grid following (GFL) and grid forming control (GFM) had been undertaken. The PHIL simulations for change in grid frequency after generation trip for different inverter based DER ratios clearly showed that both GFL and GFM with advanced control functions suppresses the drop in system frequency. Furthermore, if the inverter ratio is very high, it was possible to operate the power system stably in grid forming while the grid became unstable in grid following mode. These results suggest that grid forming inverter would become one of contributing solutions if the inverter based DER ratio increases significantly.

Additionally, different Japanese conformance tests applied to the inverter prototypes (GFM and GFL control) were used to identify the various issues in grid forming inverters. These issues had been also addressed in the STREAM project to develop suitable verification methods for grid forming inverters.

The five selected case studies have clearly shown that solar PV Systems solely or esp. in combination with storage systems are able to provide different types of frequency related grid services.

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