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ABS4TSO

Advanced Balancing Services for Transmission System Operators

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1 Kurzfassung

Der europaweit zunehmende Anteil von erneuerbaren Erzeugungsanlagen, die über Umrichtersysteme in Übertragungs- und Verteilernetze eingebunden sind, verändert das dynamische Verhalten des elektrischen Energiesystems fundamental. Während klassische Synchronmaschinen von konventionellen Kraftwerken inhärent Schwungmasse besitzen und damit dämpfend auf Frequenzabweichungen wirken, verhalten sich viele erneuerbare Erzeugungsanlagen wie Windkraft und Photovoltaik praktisch trägheitslos und tragen somit nicht zur Frequenzstabilität bei. Daher muss der zukünftige Bedarf an adäquaten Gegenmaßnahmen, die hochdynamische Reaktionen zur Kompensation dieser Effekte zur Verfügung stellen, untersucht werden. Dies beinhaltet eine detaillierte Analyse der erwarteten Systemparameter, möglicher Umsetzungsanforderungen, spezifischer Einschränkungen der analysierten Technologien und der relevanten regulatorischen Rahmenbedingungen.

Im Rahmen des Projekts *Advanced Balancing Services for Transmission System Operators (ABS4TSO)* wurden die Eigenschaften folgender schneller Regelreservekonzepte zur Unterstützung der zukünftigen Systemstabilität und -sicherheit analysiert:

- **Frequency Containment Reserve+ (FCR+),** eine neue Regelreserve ähnlich der bestehenden Primärregelreserve (Frequency Containment Reserve), aber mit wesentlich schnellerer Aktivierung,
- **Enhanced Frequency Response (EFR),** eine neue Regelreserve, die ausschließlich bei Erreichen von größeren Frequenzabweichungen mit sehr hohem Leistungsgradienten aktiviert wird,
- **Synthetic Inertia (SI),** die künstliche Bereitstellung von Momentanleistung abhängig vom Gradienten der Systemfrequenz und
- **Fast Active Power Injection (FAPI),** Leistungseinspeisung, ausgelöst durch eine große Frequenzabweichung, die kurz nach ihrer Aktivierung wieder kompensiert wird.

Zusätzlich wurden die Dämpfung von (niederfrequenten) Systemoszillationen, die schnelle Wirkleistungserholung nach Fehlern im Netz, die Dämpfung von deterministischen Frequenzabweichungen sowie die Frequenzstabilisierung im Falle eines Netzwiederaufbaus untersucht.

In diesem Bericht wird durch detaillierte Simulationen gezeigt, dass die oben genannten schnellen Regelreservekonzepte die Frequenzstabilität des zukünftigen Stromsystems verbessern und so dazu beitragen können, die Frequenz innerhalb der dynamischen Sicherheitsgrenzen zu halten.

Neben der theoretischen Analyse wurde ein Batteriespeichersystem (1 MW / 500 kWh) implementiert, um die definierten Anwendungen und Funktionalitäten in realen Feldtests zu bewerten. Die Bewertung wurde durch Laboruntersuchungen und Controller-Hardware-in-the-Loop-Tests unterstützt, mit besonderem Fokus auf die Wechselrichterfunktionalität und das Batteriemanagement, mit Hilfe eines Echtzeitsystems und eines Netzsimulators. Diese Vorgangsweise erlaubte die Durchführung sehr flexibler Analysen der zu untersuchenden

Regelreservekonzepte. Insgesamt stimmten die Ergebnisse der Feldversuche und der Laborversuche weitgehend überein. Das korrekte (d.h. spezifikationsgerechte) Verhalten der theoretisch definierten schnellen Regelleistungskonzepte konnte somit erfolgreich überprüft werden. Zur Abschätzung des Bedarfs an schnellen Regelleistungskonzepten wurde das Verhalten des zukünftigen Stromsystems simuliert. Die jeweiligen Netzsimulationen und die wesentlichen Einflussparameter basierten auf ENTSO-E TYNDP-Szenarien und den folgenden Annahmen:

- Erhöhung der Systemlast (Sektorenkopplung, EVs, Wärmepumpen, etc.)
- Verringerung der Systemträgheit (steigender Anteil an umrichterbasierter Erzeugung)
- Abnahme Selbstregeleffekts von Lasten (erhöhter Anteil an umrichterbasierten Motoren/Lasten)
- Lineare Aktivierung bestehender konventioneller FCR basierend auf den aktuellen Mindestanforderungen (vollständige Aktivierung innerhalb von 30 s)

Die Simulationen zeigen jeweils einen spezifischen Bedarf für die unterschiedlichen schnellen Regelreservekonzepte, um ein Unterschreiten der Netzfrequenz von 49,2 Hz bei Auftreten des Referenzereignisses (3000 MW) zu verhindern:

Tabelle 1: Bedarf von schnellen Regelreservekonzepten

Parameter	2030	2040
FCR+[1]	710 MW	1430 MW
EFR	620 MW	1500 MW
SI	1190 MW	2680 MW
FAPI	560 MW	1190 MW

Neben der theoretischen Entwicklung hochdynamischer Systemdienste stellt sich noch die grundsätzliche Frage, wie diese Konzepte konkret umgesetzt werden sollen. Aus regulatorischer Sicht gibt es zwei Möglichkeiten, das geforderte Systemverhalten zu erreichen. Wie unten dargestellt, kann dies entweder durch einen marktbasierten Ansatz oder durch die Festlegung spezifischer Anschlussbedingungen erfolgen:

[1] In dieser Simulation wird FCR anteilig durch FCR+ ersetzt

Abbildung 1: Optionen für die Umsetzung von schnellen Regelreservekonzepten

Für alle dargestellten Aspekte sollte das richtige Maß zwischen den Systemanforderungen, der Leistungsfähigkeit verschiedener Technologien, den Erwartungen der Marktteilnehmer und des sozialen Nutzens berücksichtigt werden. Vor diesem Hintergrund könnten nationale oder regionale Pilotprojekte unter Einbeziehung von Übertragungsnetzbetreibern, Marktteilnehmern, Herstellern und Regulierungsbehörden als vielversprechende Grundlage dienen, um die Kosteneffizienz und Effektivität verschiedener schneller Regelreservekonzepte zu demonstrieren. In Italien, Skandinavien oder Großbritannien werden ähnliche Konzepte als Marktprodukte erprobt oder bereits umgesetzt.

Basierend auf einer detaillierten marktbasierten Bewertung lassen sich folgende Schlussfolgerungen zu den unterschiedlichen schnellen Regelleistungskonzepten ableiten:

Frequency Containment Reserve+ (FCR+)

FCR+ stellt gewissermaßen eine adaptierte FCR-Funktionalität dar und könnte im Rahmen bestehender FCR-Auktionen beschafft werden, was viele Synergien ermöglichen würde. Es wird erwartet, dass das Preisniveau von FCR+ über jenem von FCR liegt und es somit eine ausreichende Marktliquidität gäbe.
Aufgrund ihres schnellen Ansprechverhaltens würde FCR+ zusätzlich die Frequenzstabilität im typischen Betriebsbereich von 50 +/- 0,2 Hz verbessern. Darüber hinaus könnte FCR+ eine interessante Alternative für Marktteilnehmer sein, die bereits an FCR-Auktionen teilnehmen. Aufgrund der höheren technischen Anforderungen an Dynamik und Überwachung könnten jedoch nur größere und hochflexible Marktteilnehmer in FCR+-Märkte eintreten.

Enhanced Frequency Response (EFR)

EFR lässt aufgrund der geforderten Charakteristik einen relativ einfachen Markteintritt für verschiedene Anbieter und Technologien und somit eine hohe Marktliquidität erwarten und erhält daher eine gute Gesamtbewertung. EFR könnte eine geeignete Alternative für viele technische Anlagen sein, die an anderen Flexibilitätsmärkten nicht teilnehmen können. Bei asymmetrischem Produktdesign (EFR/A) könnten sogar steuerbare oder schaltbare Lasten verwendet werden. EFR ist für hohe Frequenzabweichungen bei starken Asymmetrien ausgelegt und würde die Frequenzstabilität innerhalb des typischen Betriebsbereichs von 50

+/- 0,2 Hz nicht verbessern. Daher muss EFR zusätzlich zu bestehenden FCR beschafft werden. Abhängig von der verwendeten Technologie können die Optionspreise im Vergleich zu seiner seltenen Aktivierung relativ hoch sein.

Synthetic Inertia (SI)
Aufgrund der Komplexität des SI-Konzepts erscheint der Zertifikatshandel vorteilhafter als ein Ausschreibungskonzept über ein symmetrisches Produktdesign. Damit wäre auch ein faires Gleichgewicht zwischen Technologien, die inhärent Schwungmasse bereitstellen (z. B. Synchrongeneratoren), und speziell angepassten Systemen (z. B. Batterien) gewährleistet. SI muss zusätzlich zur bestehenden FCR beschafft werden und der Aufbau dieses neuen Zertifikatsmarktes würde natürlich erhebliche Anstrengungen für Handels- und Überwachungsprozesse erfordern. Andererseits dürften Inertia-Zertifikate eine hohe Marktliquidität generieren und SI würde zusätzlich die Frequenzstabilität unterstützen.

Fast Active Power Injection (FAPI)
Aufgrund der einfachen technischen Voraussetzungen könnte FAPI für viele Marktteilnehmer eine Alternative darstellen, die an anderen Flexibilitätsmärkten nicht teilnehmen können (z. B. Windenergieanlagen oder Wärmepumpen). Seine statische und unkontrollierte Aktivierung erfordert jedoch zusätzliche Sorgfalt bei der Bestimmung des geeigneten (individuellen) Auslösers und der regionalen Verteilung der beteiligten Anlagen, um die (lokale) Systemstabilität sicherzustellen. FAPI ist für hohe Frequenzabweichungen bei starken Ungleichgewichten ausgelegt und würde die Frequenzstabilität innerhalb des typischen Betriebsbereichs von 50 +/- 0,2 Hz nicht verbessern. Daher muss FAPI zusätzlich zum bestehenden FCR beschafft werden und abhängig von der verwendeten Technologie können die Optionspreise im Vergleich zur seltenen Aktivierung relativ hoch sein.

1.1 Empfehlungen

Die Ergebnisse des Projekts ABS4TSO zeigen, dass die Auswirkungen von Umrichtersystem auf das Stromsystem in der Zukunft höchstwahrscheinlich Gegenmaßnahmen und Änderungen des aktuellen regulatorischen Rahmens erfordern werden.

Notwendige Änderungen des betroffenen Rechtsrahmens werden dabei mehrere Jahre dauern, bis sie auf nationaler Ebene in Kraft treten. Um den zukünftigen Systemanforderungen gerecht zu werden, ist es daher erforderlich, die notwendigen Änderungsinitiativen auf europäischer Ebene rechtzeitig zu starten.

Aus Systemsicht wäre es daher sinnvoll, eine transparente Umsetzungs-Roadmap für das kontinentaleuropäische Synchrongebiet zu entwickeln:

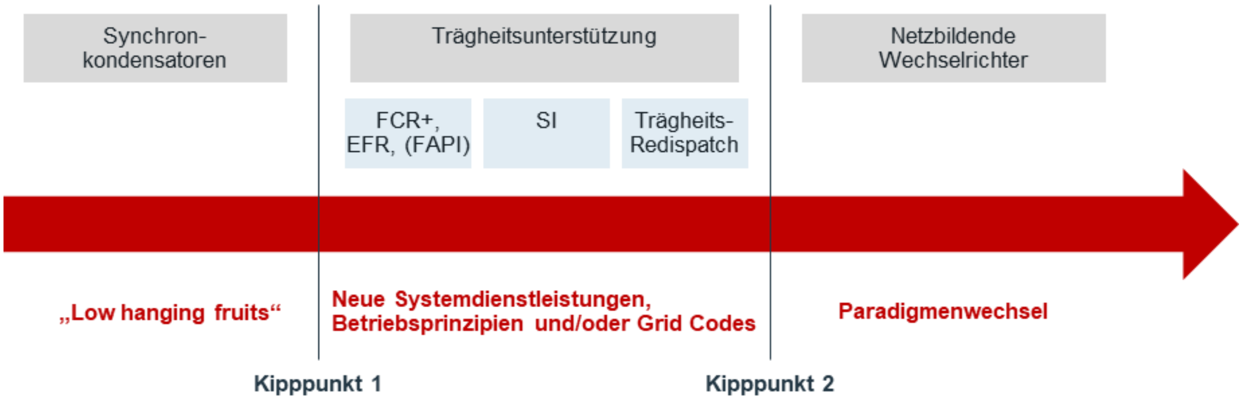


Abbildung 2: Beispielhafte Umsetzungs-Roadmap

Diese enthält Gegenmaßnahmen, die in drei Gruppen unterteilt werden können:

Schnell umsetzbare Gegenmaßnahmen („Low Hanging Fruits")

Der schnelle Wandel im Stromsystem sowie Bedenken hinsichtlich des Trägheitsverlusts haben neues Interesse an rotierenden Phasenschiebern geweckt. Rotierende Phasenschieber bieten eine alternative Quelle für Trägheit zur Stabilisierung des Netzes. Ein großer Vorteil von rotierenden Phasenschiebern ist, dass sie eine sehr kostengünstige und zuverlässige Möglichkeit sind, die Frequenzstabilität in Netzen mit geringer Trägheit aufrechtzuerhalten, während sie auch zusätzliche Funktionalitäten für Netzbetreiber (z. B. Blindleistungsmanagement oder Kurzschlussleistung) bereitstellen können.

Neue Systemdienstleistungen, Betriebsprinzipien und/oder Grid Codes

FCR+, EFR (asymmetrisch) oder Inertia-Zertifikate haben grundsätzlich die höchste Eignung als zukünftige Marktprodukte, da es verschiedene Synergien mit bereits bestehenden Regelreservemärkten gibt. Ein zusätzlicher Vorteil solcher Marktprodukte besteht darin, dass sie auch von bestehenden Anlagen bereitgestellt werden könnten. Darüber hinaus können auf EU-Ebene mögliche Ansätze der schnellen Regelreservekonzepte EFR, FAPI und SI als Netzanschlussbedingungen für das kontinentaleuropäische Synchrongebiet implementiert werden. Zur Einführung neuer Marktprodukte oder harmonisierter Grid-Code-Anforderungen ist es jedoch erforderlich, die notwendigen Initiativen auf europäischer Ebene rechtzeitig zu starten.

Paradigmenwechsel (Grid Forming)

Die meisten Wechselrichtersteuerungen sind heute netzfolgend („Grid Following"). Solche Steueransätze liefern dem System nicht inhärent eine Trägheitsreaktion und können als Hauptursache für potenzielle Frequenzinstabilitäten angesehen werden. Diese Einschränkung hat eingehende Untersuchungen zu netzbildenden Steuerungsverfahren für neue leistungselektronische Wechselrichter beschleunigt, die Funktionalitäten bereitstellen, die traditionell von Synchronmaschinen bereitgestellt werden. Die praktische Umsetzung der Fähigkeit zur Netzbildung („Grid Forming") befindet sich derzeit in der Entwicklung und erfordert umfangreiche Vorstudien in Zusammenarbeit mit Experten und Herstellern, um harmonisierte Spezifikationen für das gesamte Stromsystem zu etablieren.

2 Executive Summary

The extraordinary increase of renewable generation units in Europe connected to the transmission and distribution grid via inverter systems has a high impact on the dynamic behaviour of the energy system. In contrast to conventional synchronous machines, which dampen frequency deviations due to their inherent inertia, such inverter-connected generation units, like wind and photovoltaics, act inertia-free and therefore do not support frequency stability. Hence, the future need for adequate countermeasures providing highly dynamic reactions to compensate these effects needs to be assessed. This includes a detailed analysis of the expected system parameters, possible implementation requirements, specific limitations of the analysed technologies and the relevant regulatory framework.

Within the scope of the project *Advanced Balancing Services for Transmission System Operators (ABS4TSO)*, the characteristics of the following fast control reserve concepts, supporting future system stability and security, were analysed:

- **Frequency Containment Reserve+ (FCR+)**, a new control reserve similar to existing frequency containment reserve, but with significantly faster activation,
- **Enhanced Frequency Response (EFR)**, a new control reserve activated very quickly during larger frequency excursions,
- **Synthetic Inertia (SI)**, the artificial provision of instantaneous power following gradients in the system frequency and
- **Fast Active Power Injection (FAPI)**, a power burst triggered by a large frequency deviation which is compensated moments after its activation.

Additionally, the dampening of (low frequency) oscillations, the repowering of the system after disturbances, the attenuation of Deterministic Frequency Deviations (DFDs) and the frequency stabilization following a blackout were evaluated.

As presented in this report and shown by detailed simulations, the above-mentioned fast control reserve concepts can improve the frequency stability of the future power system and can thus help to keep the frequency above the dynamic security limits.

In addition to the theoretical analysis, a battery storage system (1 MW / 500 kWh) was installed as a reference implementation in order to assess the defined applications and functionalities in dedicated field tests. The installation of the battery storage system was supported by laboratory and controller hardware-in-the-loop tests, with special focus on inverter functionality and battery management with the help of a real-time system and a grid simulator. This allowed for the fast control reserve concepts to be tested in a flexible environment. Overall, the results of the field tests and the laboratory tests were largely coherent and it was possible to assess the correct behaviour (i.e., according to specification) of the theoretically defined fast control reserve concepts. For the estimation of the demand for fast control reserve concepts, the behaviour of the future power system was simulated. The respective power system simulations and the main influencing parameters were based on ENTSO-E TYNDP scenarios and the following assumptions:

- Increase of system load (sector coupling, EVs, heating pumps, etc.)
- Decrease of system inertia (increasing share of inverter based generation)
- Decrease of self-regulating effect of loads (increased share of inverter based motors/loads)
- Linear activation of existing conventional FCR based on the current minimum requirements (full activation within 30 s)

The simulations show a specific demand for each of the different fast control reserve concepts, in order to keep the system frequency in a reference incident (3000 MW) above 49.2 Hz:

Table 2: Necessary amounts of fast control reserves

Parameter	2030	2040
FCR+[2]	710 MW	1430 MW
EFR	620 MW	1500 MW
SI	1190 MW	2680 MW
FAPI	560 MW	1190 MW

Besides the theoretical development of highly-dynamic system services, the question arises how they should be introduced in a power system. From a regulatory point of view, there are two ways to achieve the required system behaviour. As shown below, this can be done either by a market-based approach or by establishing specific connection requirements:

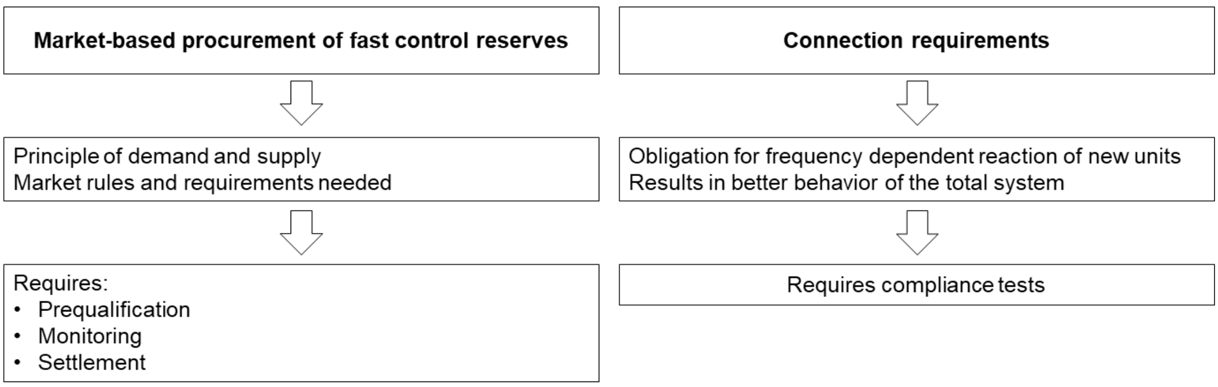


Figure 3: Options for the implementation of fast control reserves

For all possible aspects, there is a need to consider a balance between the system needs, the capability of different technologies, the expectations from market participants and social welfare. Considering this, national or regional pilot projects, including TSOs, market participants, manufacturers and regulators, could serve as a promising basis to demonstrate the cost-efficiency and effectiveness of different fast control reserve concepts. In fact similar concepts are tested or already implemented as market products in Italy, Scandinavia or Great Britain.

[2] In this simulation FCR+ would substitute conventional FCR

Based on a detailed market based evaluation the following conclusions regarding the different fast control reserve concepts can be derived:

Frequency Containment Reserve+ (FCR+)

FCR+ could be procured as part of existing FCR auctions, which would open up many synergies. The FCR+ price level is expected to be above FCR prices and thus would lead to sufficient market liquidity.
Due to its fast response characteristics FCR+ would additionally improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Furthermore, FCR+ could be an interesting alternative for market participants, which already take part in FCR auctions. However, due to the higher technical requirements regarding the dynamics and monitoring only larger and highly flexible market participants would be able to enter into FCR+ markets.

Enhanced Frequency Response (EFR)

EFR gets a good overall rating due to easy market entry for various providers and technologies as well as an expectable high market liquidity. EFR could be a suitable alternative for many technical facilities, which cannot take part in other flexibility markets. In case of asymmetric product design (EFR/A) even controllable or switchable loads could be used. EFR is designed for high frequency deviations in case of severe imbalances and would not improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Therefore, EFR has to be procured additionally to existing FCR and depending on the applied technology, option prices could be relatively high compared to its infrequent activation.

Synthetic Inertia (SI)

Due to the complexity of the concept of SI, certificate trading appears to be more advantageous than a tender concept via a symmetrical product design. This would also ensure a fair balance between technologies, which inherently provide inertia (e.g. synchronous generators) and specifically adapted systems (e.g. batteries). SI has to be procured additionally to existing FCR and the setup of this new certificate market would naturally require substantial efforts in trading and monitoring processes. On the other hand, inertia certificates will likely generate high market liquidity and SI would additionally support the frequency stability.

Fast active power injection (FAPI)

Because of its simple technical requirements, FAPI could be an alternative for many market participants, which cannot take part in other flexibility markets (e.g. wind turbines or heat pumps). However, its static and uncontrolled activation requires additional care for the determination of the appropriate (individual) trigger and the regional distribution of participating units, to ensure (local) system stability. FAPI is designed for high frequency deviations in case of severe imbalances and would not improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Therefore, FAPI has to be procured additionally to existing FCR and depending on the applied technology, option prices could be relatively high compared to its infrequent activation.

2.1 Recommendations

The results of the project ABS4TSO show that at some point in the future, the impact of inverter systems on the power system will most likely require countermeasures and amendments in the current regulatory framework.

Due to the formal process, necessary amendments of the relevant regulatory framework would take several years until they enter into force on a national level. In order to meet the future system needs it is therefore required to start the necessary amendment initiatives on a European level early enough.

From a system point of view, it would therefore be beneficial to develop a transparent implementation roadmap for the CE power system:

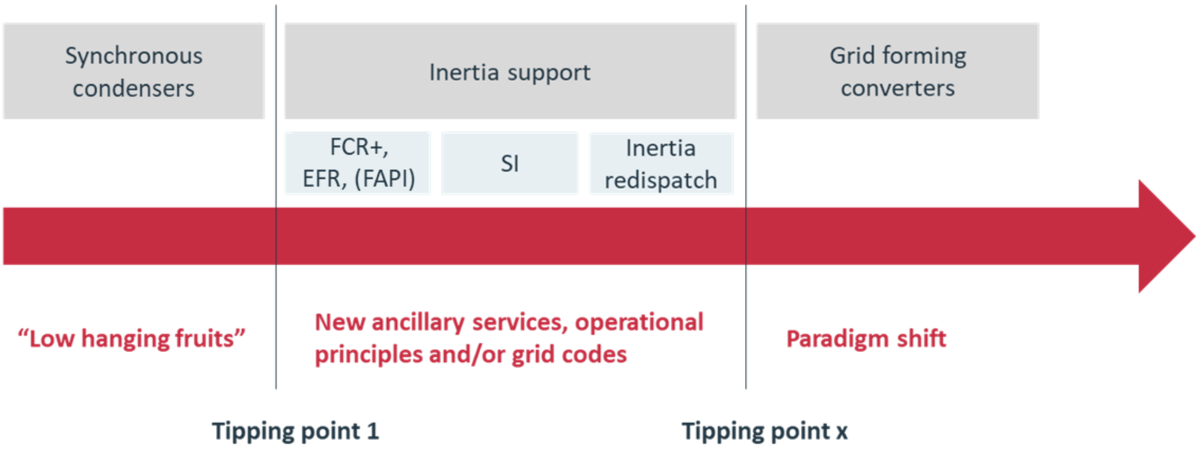


Figure 4: Exemplary implementation roadmap

As depicted above, the different proposed countermeasures can be categorized in different groups:

Countermeasures, which can be quickly implemented ("low hanging fruits")
The rapid change of power systems and concerns over the loss of inertia have stimulated new interest in synchronous condensers (SC). SC can mimic the operation of large conventional power plants by providing an alternative source of spinning inertia to stabilize the grid. A major advantage of SCs 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).
New ancillary services, operational principles and/or grid codes
FCR+, EFR (asymmetric) or inertia certificates basically have the highest suitability as future market products as there are several synergies with already existing balancing markets. 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 EFR, FAPI and SI can be found on EU-level as grid connection rules for the CE power system and used as potential starting points. However, in order to introduce new market products or harmonized grid code requirements it is required to start the necessary amendment initiatives on a European level early enough.

Paradigm shift (grid forming)

Most inverter controllers today are grid-following and built on the assumption that system voltage and frequency are regulated by inertial sources. Such control approaches do not inherently provide an inertial response to the system and could be seen as the “root-cause” for potential frequency instabilities. This limitation has accelerated in-depth investigations into grid-forming control methods for new power electronic inverters, which provide functionalities that are traditionally provided by synchronous machinery. The practical implementation of grid-forming capability is currently under development and requires extensive preliminary studies in cooperation with experts and manufacturers, in order to establish harmonized specifications for the whole power system.

3 Contents

4 Introduction

The extraordinary increase of renewable generation units in Europe connected to the transmission and distribution grid via inverter systems has a high impact on the dynamic behaviour of the energy system. In contrast to conventional synchronous machines, which dampen frequency deviations due to their inherent inertia, such inverter-connected generation units, like wind and photovoltaics, act inertia-free and therefore do not support frequency stability. Hence, the future need for adequate countermeasures providing highly dynamic reactions to compensate these effects needs to be assessed. This includes a detailed analysis of the expected system parameters, possible implementation requirements, specific limitations of the analysed technologies and the relevant regulatory framework.

4.1 Goals and methodological approach

Within the scope of the project Advanced Balancing Services for Transmission System Operators (ABS4TSO), the characteristics of fast control reserve concepts, supporting future system stability and security were analysed. To achieve the project goals, the defined project structure ensures a structured analysis at the system level and at the plant level. Research was done along the development of the technology readiness levels. This includes simulation, laboratory analysis and field tests. The latter were conducted using a battery storage system. Due to their characteristics, battery storage systems are suitable to provide highly-dynamic reactions. A battery storage system (1 MW / 500 kWh) was installed as a reference implementation in order to assess the defined applications and functionalities.

4.2 Project structure

The project ABS4TSO received funding from the Austrian Research Promotion Agency (FFG) under the 4th call of the Energy Research programme.
It started in May 2018 and was completed in December 2021. It was divided into five work packages. The first being project management, the four other ones are explained in the next section.
A consortium, representing a broad spectrum within the Austrian Energy sector, conducted the research project:

- Austrian Power Grid AG is an Austrian independent transmission system operator. One of its core responsibilities is to maintain the supply-demand balance at all times.
- The Institute of Energy Systems and Electrical Drives at the Technische Universität Wien has a strong academic record in the integration of renewable energy into the power system.
- The AIT Austrian Institute of Technology is Austria's largest research and technology organisation. Among the European research institutes, AIT is a specialist in the energy infrastructure issues of the future.

- VERBUND Hydro Power GmbH is one of the largest producers of hydropower in Europe.
- VERBUND AG's[3] organisational unit Corporate Innovation & New Business has a focus on new energy storage and innovative energy solutions and services in general.
- VERBUND Energy4Business GmbH[4] is responsible for the short and long term energy trading.

4.3 Structure of this report

This report summarizes the results of the project ABS4TSO. It is structured in the following manner:

- Recommendations and an executive summary are given in chapters 1 and 2, in German and English, respectively[5].
- Each of the chapters 5-8 contain a detailed description of contents[6] of one or two work packages (WP) and a section with conclusions[7] at the end:
  - WP 2 gives a detailed analysis of the scenarios for the future power system. In addition, different technology options were assessed regarding there suitability for the provision of frequency-control-services.
  - WP 3 comprises the development of functions for the mitigation of different frequency events.
  - WP 4 summarizes the laboratory and controller hardware-in-the-loop tests that were conducted.
  - The results of the field tests are discussed in WP 5.
  - The findings of WP 6 include recommendations for a future implementation of the fast control reserve concepts, which were developed and evaluated in previous work packages.

[3] Name at the beginning of the project VERBUND Solutions GmbH
[4] Name at the beginning of the project VERBUND Trading GmbH
[5] corresponds to 'Ausblick und Empfehlungen' in template
[6] corresponds to 'Inhaltliche Darstellung' in template
[7] corresponds to 'Ergebnisse und Schlussfolgerungen' in template

5 System analysis and function development

5.1 Introduction WP2 & WP3

With the ongoing transformation of the electric system, aiming at reducing emissions and increasing the share of renewable energies, several challenges arise in regard to maintaining operational security and frequency stability. Most of these are tied to the decreasing system inertia expressed through the network time constant.

One of the goals of WP2 is the definition of scenarios (see Section 5.2) based on current considerations and expected future trends regarding the system inertia and its impact on the design hypothesis used for evaluation of the system dynamics. Based on these scenarios the corresponding values of the frequency nadir and frequency gradient as well as the necessary demand for frequency-control-services to maintain frequency stability are to be determined (see Section 5.5).

WP3 focuses on defining the frequency events and the frequency-control-services to be investigated as well as analyzing the simultaneous provision of different functions. Section 5.3 gives a brief overview of the different frequency events to be investigated such as low-frequency oscillations and deterministic frequency deviations (DFDs). Section 5.4 introduces the frequency-control-services, their aim, and their general characteristics as well as a detailed specification of their respective time- and frequency-characteristic curves and their parametrization. Section 5.6 discusses the different aspects regarding the simulation-based development of functions. Section 5.7 presents the considerations for a combined provision of frequency-control-services and describes possible synergies as well as difficulties. As already mentioned, Section 5.8 gives an overview of the technology potential analysis, which aims to assess the capability of different technologies at providing selected frequency-control-services.

5.2 Scenarios

This Section presents the scenarios used to conduct the different simulations as part of WP2 and WP3. The scenarios are defined by specifying the values of the system parameters: system size, self-regulating-effect of the loads and time constant, as well as the size of the reference incident. The values of these parameters are chosen in accordance with the so-called classical design hypothesis of the ENTSO-E [1, 2] and are listed in Table 3 below.

Table 3: System parameters – classical design hypothesis [1, 2]

Parameter	Value
Power imbalance	±3000 MW
System size	150 GW
Self-regulating-effect of the loads	1 %/Hz

Time constant	10 s

In addition to the values from Table 3 adapted values for the time constant are taken into account based on the predicted yearly duration curves of the time constant for the years 2030 and 2040, which can be seen in Figure 5. As shown, the estimated values for the time constant range from 1.5 to 9 s. Figure 6 shows the resulting frequency curves following a reference incident for different values of the time constant.

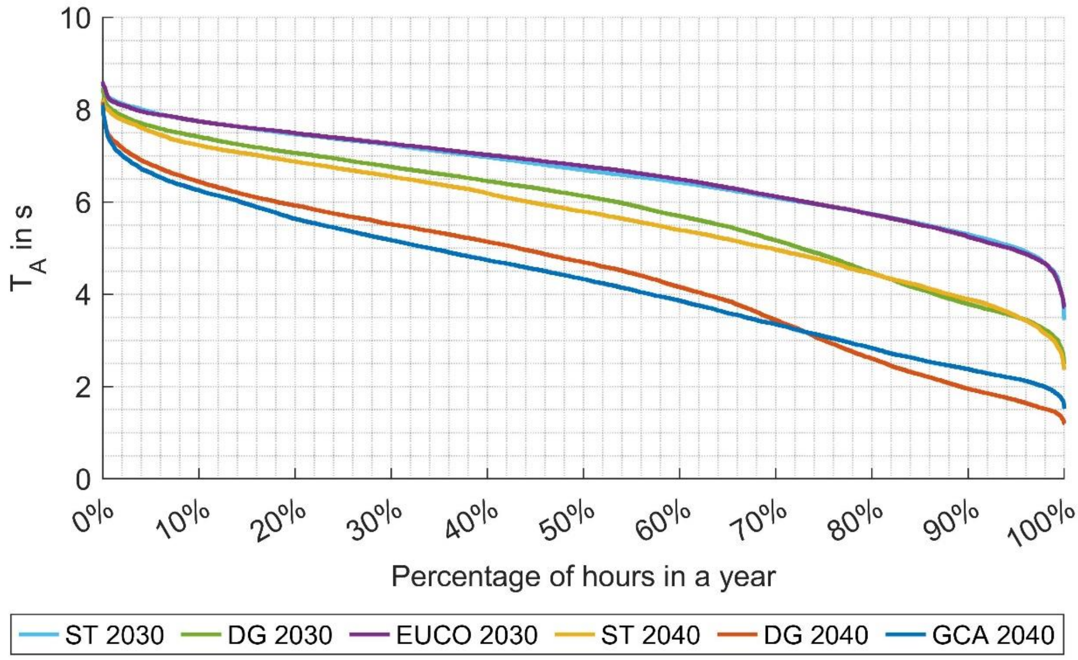


Figure 5: Yearly duration curve of the time constant

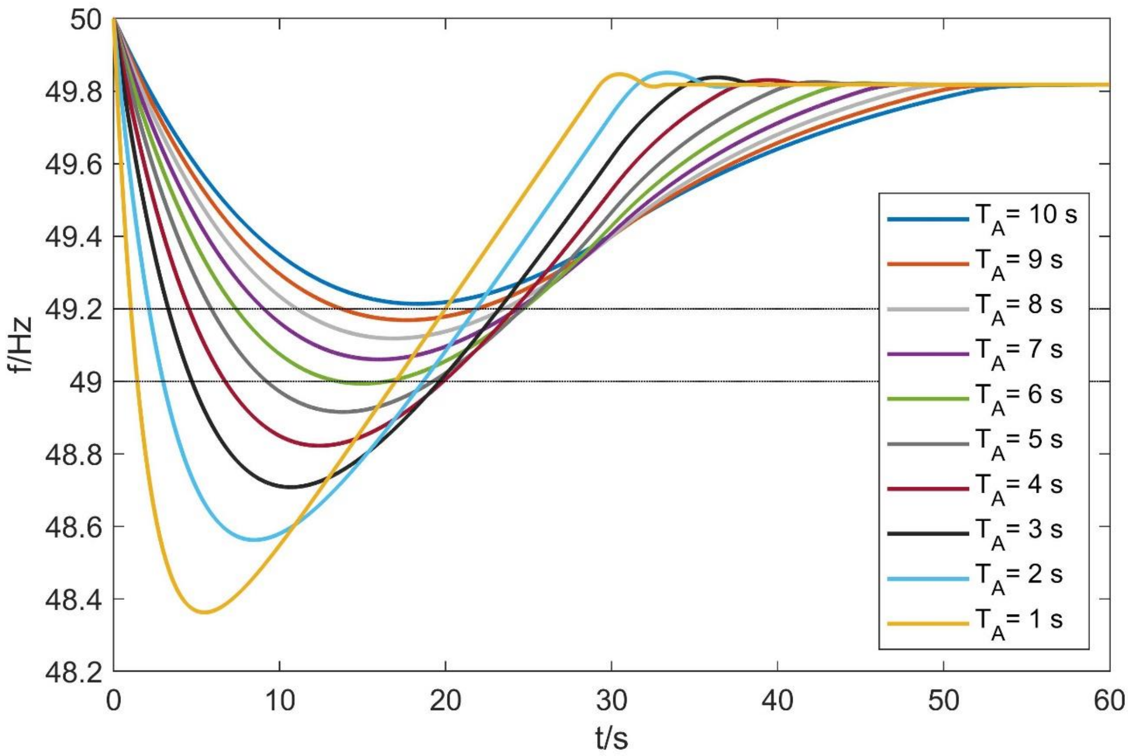


Figure 6: Frequency curves following a reference incident for different values of T_A

Consequently, most of the simulations in WP2 and WP3 are carried out with the values from Table 3 and different values of T_A within the range of 2 s to 10 s. However, to keep this document concise, the following sections only present the results with a time constant of 6 s. This value is chosen, because the predicted values of the time constant are below 6 s for a significant portion of the year and for a time constant of T_A =6 s the frequency nadir drops below 49 Hz, as can be seen in Figure 6, which would result in frequency dependent load shedding.

Since the main goal of introducing additional frequency-control-services is maintaining frequency stability and avoiding frequency dependent load shedding, the relevant KPIs for the frequency-control-services are the frequency nadir, the necessary demand as well as the findings regarding scalability and frequency quality.

5.3 Frequency events investigated

Within the scope of the project, the following three types of frequency events are investigated:

- Frequency excursions following a reference incident
- Low-frequency oscillations
- Deterministic frequency deviations

Frequency excursions following a reference incident are investigated via simulations with a single area model of the Regional Group Continental Europe (RGCE) and models of the different frequency-control-services. The main goals of these simulations are to estimate the effect of the transformation of the electric system, to assess the capability of the frequency-control-services to maintain frequency stability and to get an insight on their appropriate parametrization and suitability for a system level use in the RGCE. The results of these simulations make up a significant portion of the following chapters and are also part of several papers [3-5].

The low-frequency oscillations are examined via a multi-area model (simulations have been conducted with 2- and 3-area models). The main goals of these simulations are to investigate the impact of the system parameters (mainly the time constant) and the frequency-control-services on low-frequency oscillations. Subsection 5.6.2 will give an overview of the results presented in [6].

Finally, the deterministic frequency deviations are investigated via an expanded version of the single-area model of the RGCE, which allows a closed loop simulation using real frequency data. The main goals of these simulations are to analyze real frequency excursions and to capture the main characteristics of DFDs as well as to develop a frequency-control-service specifically aimed at limiting these DFDs. The results of these simulations are presented in subsection 5.6.4.

5.4 Detailed specification of the different frequency-control-services

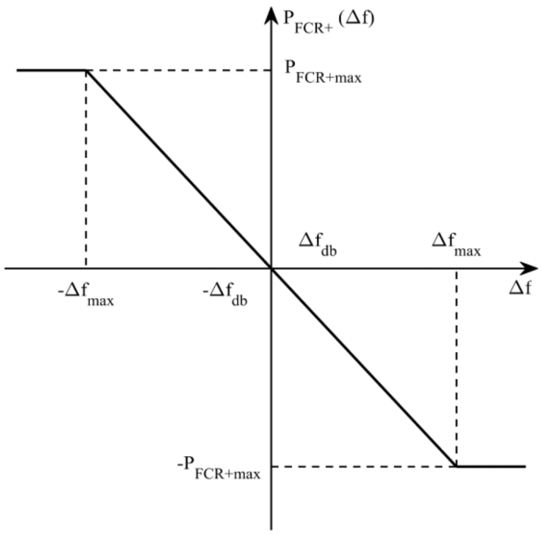
This chapter provides a detailed specification of the four different frequency-control-services examined in this project:

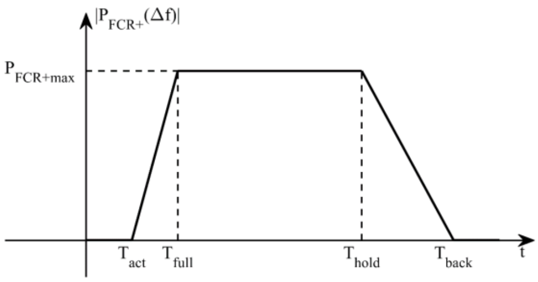
- Frequency Containment Reserve+ (FCR+),
- Enhanced Frequency Response (EFR),
- Synthetic Inertia (SI) and
- Fast Active Power Injection (FAPI)

including their respective frequency- and time-characteristic curves as well as their parametrization.

5.4.1 Frequency Containment Reserve+ (FCR+)

FCR+ represents a faster version of the current FCR and is designed to also replace a portion of the current FCR power. This way, it would be possible to maintain frequency stability with the existing frequency regulation structure, by simply utilizing the ability of certain technical units to provide FCR with a shorter full activation time. Therefore, most of the properties of FCR+ match the ones of FCR, except the already mentioned full activation time and the nominal power. Similarly, the frequency- and time-characteristic curves of FCR+, which are shown in Figure 7, are also largely identical with the frequency- and time-characteristic curves of FCR.





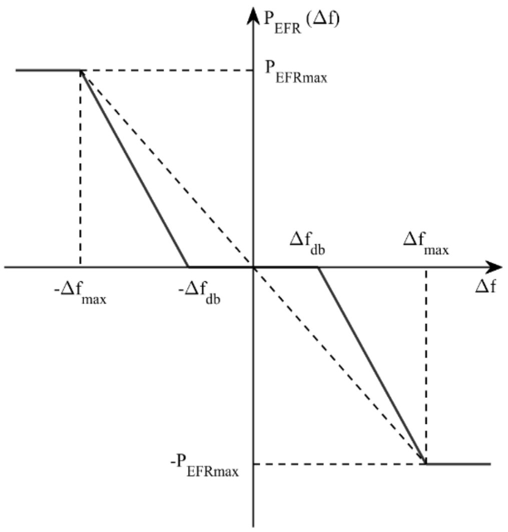
Parameter	Unit	Reference value	Interval
$P_{FCR+max}$	MW	-	-
Δf_{db}	Hz	0	(0;0.01)
Δf_{max}	Hz	0.2	(0;0.2)
T_{act}	s	0.5	(0;1)
T_{full}	s	T_{act} + 5	(0.5;15)
T_{hold}	s	T_{full} + (15*60 or 30*60)	(15*60;∞)
T_{back}	s	T_{hold} + 10	(15*60;∞)

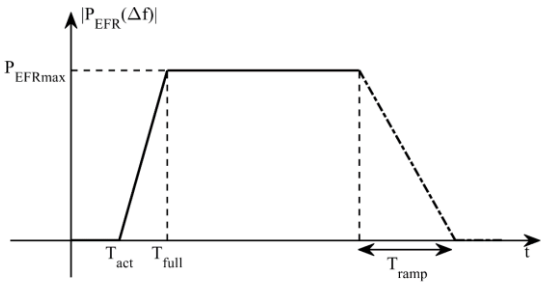
Figure 7: Frequency- and time-characteristic curves of FCR+

The nominal power of FCR+ results from the requirement to maintain a frequency nadir above 49.2 Hz and therefore differs depending on the investigated scenario. For the scenario with values according to the classical design hypothesis and the reference incident (see WP2 report) as well as an adapted time constant of 6 s the necessary FCR+ power amounts to 1130 MW. Consequently, the FCR power equals 1870 MW so the sum of the two frequency-control-services FCR and FCR+ remains 3000 MW.

5.4.2 Enhanced Frequency Response (EFR)

EFR represents a fast frequency-control-service designed to mitigate large frequency excursions caused by events like the reference incident. Its main purpose is to stabilize the system and support FCR during large frequency excursions. The frequency- and time-characteristic curves of EFR including the parameter values are depicted in
Figure 8.





Parameter	Unit	Reference value	Interval
P_{EFRmax}	MW	-	-
Δf_{db}	Hz	0.2	(0.2;0.5)
Δf_{max}	Hz	0.5	(0.5;0.8)
T_{act}	s	0.5	(0;1)
T_{full}	s	T_{act} + 0.5	(0.5;5)
T_{ramp}	s	5	(0.5;60)

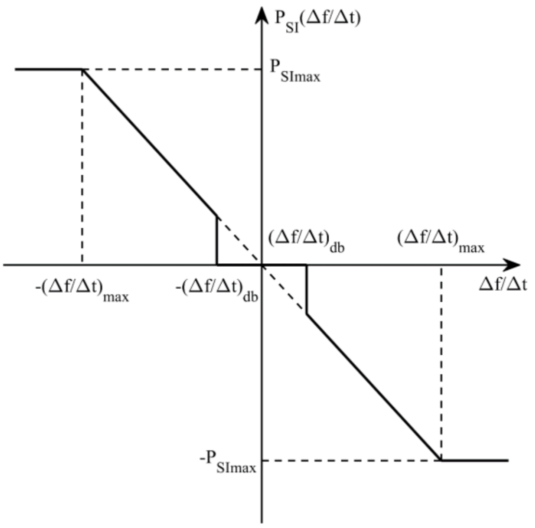
Figure 8: Frequency- and time-characteristic curves of EFR

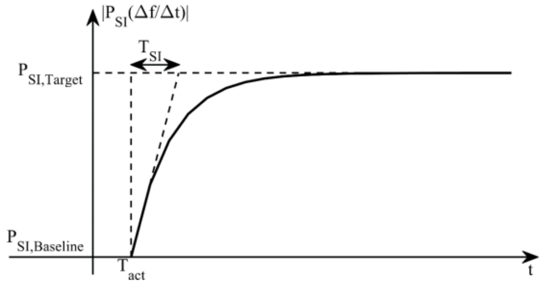
As shown in
Figure 8, the frequency-characteristic curve of EFR is designed with a frequency deadband of 200 mHz resulting in an activation once the frequency deviation surpasses the full activation frequency of FCR and FCR+. Furthermore, it is designed without a discontinuity around the frequency deadband, to avoid immediate power changes. Finally, the time-characteristic curve only defines the ramp times for activating and deactivating EFR, but the definition of a hold time is not intended, since frequency deviations >200 mHz are not expected to last longer than a minute at most.

5.4.3 Synthetic Inertia (SI)

SI represents a frequency-control-service designed to imitate the behavior of synchronous generators and thus counteract the decreasing system inertia and time constant. This is achieved by SI reacting to the frequency gradient, rather than to the frequency deviation. The frequency-gradient- and time-characteristic curves of SI are depicted in
Figure 9.

Since SI only imitates the behavior 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 as presented in [5] and illustrated in Figure 10. The effect of this zone-selective control is shown in Figure 11 where the dashed line shows the power and frequency-curves with and the solid line without a zone-selective-control.





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 9: Frequency- and time-characteristic curves of SI

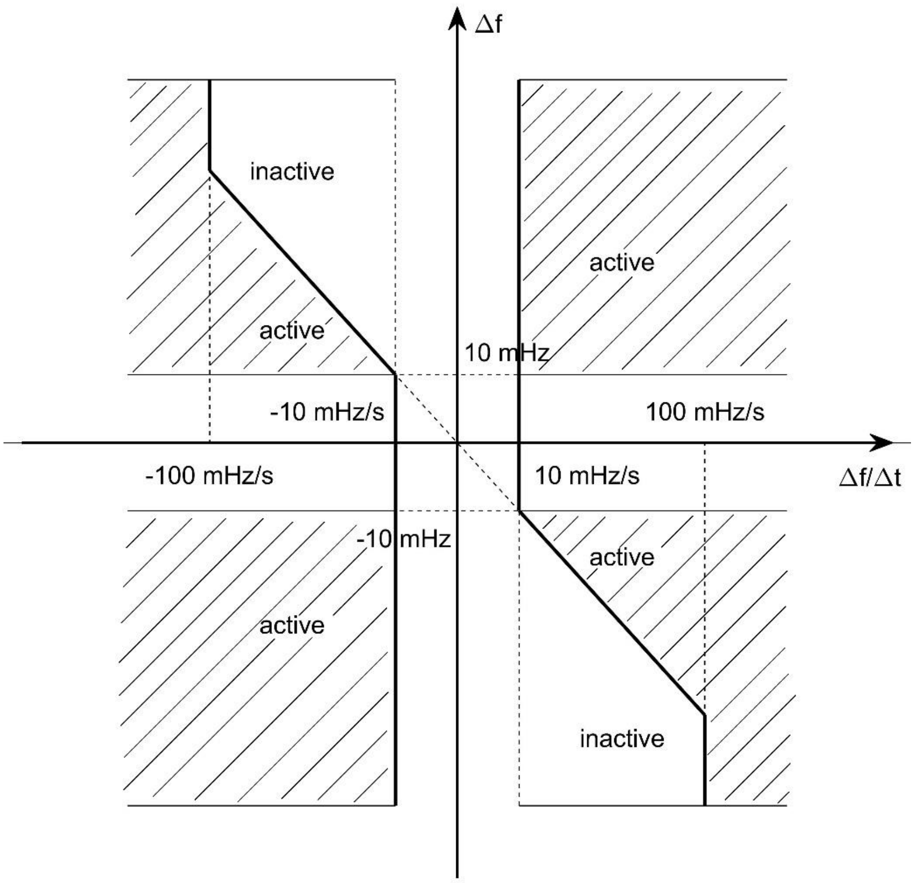


Figure 10: Zone-selective-control of SI

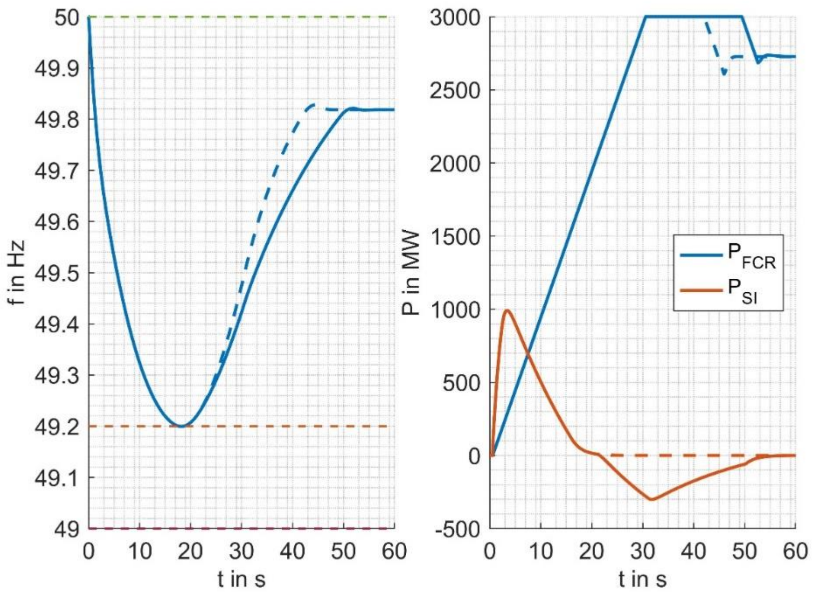
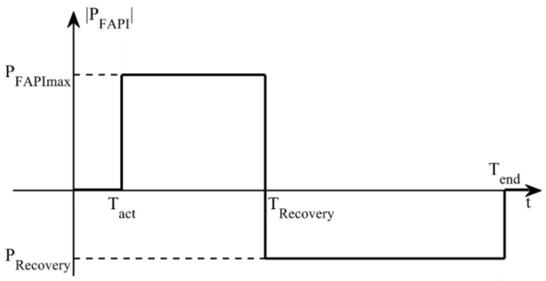


Figure 11: Frequency- and power-curves for SI

5.4.4 Fast Active Power Injection (FAPI)

FAPI represents a frequency-control-service designed to support the system for a short duration in case of large frequency excursions. It is designed to be energy neutral, which means, that FAPI providing units support the system after an imbalance occurs by providing or withdrawing energy from the grid and at a later point (optimally once the frequency has at least partially recovered) withdrawing or feeding in the same amount of energy. This also means that the behavior of FAPI is independent of the current frequency deviation once it has been activated. Consequently, FAPI does not have a frequency-characteristic curve, it only has a frequency threshold (set at 200 mHz), which triggers a defined time behavior. This time behavior of FAPI is shown in
Figure 12.



Parameter	Unit	Reference value	Interval
$P_{FAPImax}$	MW	-	-
$P_{Recovery}$	MW	$P_{FAPImax}$ / 2	(0; $P_{FAPImax}$ / 2)
Δf_{db}	Hz	0.2	(0.01;0.3)
T_{act}	s	0.5	(0;1)
$T_{Recovery}$	s	T_{act} + 15	(5;20)
T_{end}	s	$T_{Recovery}$ + ($T_{Recovery}$ - T_{act}) * 2	(10;60)

Figure 12: Time behavior of FAPI

Since FAPI is an energy neutral frequency-control-service, the energy in the first provision phase must match the energy in the so-called recovery phase.

5.5 Demand for frequency-control-services

In Section 5.2, Figure 6 already introduced the frequency curves following a reference incident for different values of the time constant. This section focuses on the necessary demand of the different frequency-control-services to maintain frequency stability. Additionally, the frequency-control-services are investigated regarding their scalability to determine, whether they are suited for a system level deployment in the RGCE. The necessary demand for each frequency-control-service is defined as the minimal amount of power needed to keep the frequency nadir above 49.2 Hz. The resulting values from the simulations for each frequency-control-service for a scenario according to Table 3 with a time constant of 6 s are listed in Table 4. Figure 13 shows the corresponding frequency and power curves following a reference incident for each frequency-control-service.

Table 4: Demand for different frequency-control-services

Frequency-control-service	Demand [MW]
FCR+	1130
EFR	630
SI	1440
FAPI	630

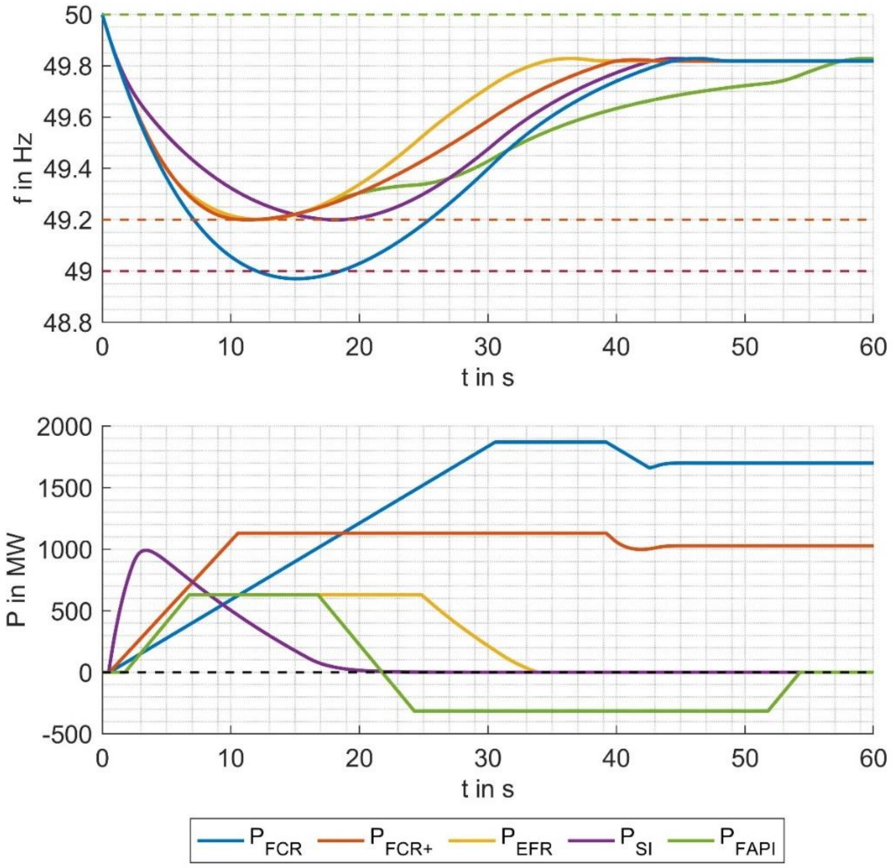


Figure 13: Frequency and power curves for the investigated Frequency-Control-services

The simulation results show that FCR+ can help maintain stability and improve frequency quality with a reasonable amount of regulating power. Furthermore, FCR+ shows good scalability and suitability for a system level deployment in the RGCE and therefore constitutes a good option for a new frequency-control-service.

Similar to FCR+, the simulation results for EFR also show that it can help maintain stability and improve frequency quality in case of critical frequency events. Furthermore, it also shows good scalability and suitability for a system level deployment in the RGCE. Compared to FCR+, the necessary amount of EFR power is lower because of the shorter full activation time. However, EFR constitutes an additional regulating power in the system and is only active in case of critical frequency events, while FCR+ also provides benefits regarding frequency quality during normal operation and would be part of the current 3000 MW for FCR. Nevertheless, EFR constitutes a good addition to the existing frequency-control structure especially against critical frequency events.

The simulations show that SI can successfully counteract the decreasing system inertia and time constant and therefore delay the frequency nadir thus providing a positive impact on frequency quality and helping to maintain frequency stability in the system. Furthermore, SI also proves to offer good suitability and scalability for a system level use in the RGCE. However, since the presented parametrization is mainly intended for critical frequency events, further research is necessary on the proper parametrization of SI to achieve a reasonable effectiveness for both normal operation and critical frequency events.

While the simulations show that FAPI can help mitigate the frequency deviation in case of critical frequency events, they also show that the parametrization of FAPI is cumbersome, and its use can have a negative impact on the frequency quality because of the distinct second frequency nadir. Combined with the absence of a frequency dependent behavior FAPI does not offer good scalability and is therefore not suited for a system level use in the RGCE.

In summary, according to the simulations and the excerpt of the results shown in Figure 13, FCR+, EFR and SI prove to offer good scalability and suitability for a system level deployment in the RGCE and could therefore be considered as new frequency-control-services. FAPI on the other hand shows positive aspects for maintaining frequency stability, but due to its uncontrolled nature it does not offer good scalability and should therefore not be considered for a system level use in the RGCE.

5.6 Simulation-based development of functions

This chapter focuses on different aspects of the simulation-based development of functions, such as frequency measurement, low frequency oscillations, blackouts, or repowering of the system.

5.6.1 Frequency measurement

The activation of frequency reserves such as described in Section 5.4 depends on the actual frequency that is measured locally at the connection point of the corresponding technical entity providing such reserves. Especially for highly-dynamic frequency reserves, the delay of the corresponding frequency measurement device, therefore, plays an important role. Several phenomena may disturb this local frequency measurement, which are mainly generated by phase jumps induced by discontinuities near the local frequency measurement node, including short circuits or topology changes that involve circuit breaker or disconnector maneuvers. Since highly-dynamic frequency reserves are designed to stabilize the frequency in the interconnected network in form of a solidary process, such “wrongly” measured local frequency may lead to a situation where frequency reserves are activated without the global need of frequency stabilization in the network. In order to distinguish between the frequency measured locally at technical entities and the frequency that indicates a need for frequency stabilization, ENTSO-E [7] uses the term “mean frequency of the system”, which may be interpreted as mean value over all local frequency measurements in the network. However, besides the difference between local frequency measurements and such a mean frequency of the system, especially large interconnected networks show a pronounced effect of propagation delay after a perturbation influencing the frequency. Therefore, larger areas in an interconnected network may have different corresponding “mean frequencies of the area”, indicating the global need for frequency stabilization in the same way as described for the mean frequency of the system above. However, the propagation delay between different areas may lead to inter-area oscillations due to unfavorable activation of frequency reserves. In summary, the frequency measurement as input signal for the activation of frequency reserves faces two problems. The first problem of local effects such as short circuits and topology changes, and the second problem of unfavorable activation of frequency reserves to prevent oscillations. Both problems may be addressed through appropriate filtering methods. However, there is a trade-off between time delay induced by filtering and accuracy of the measurement. The shorter the time for frequency calculation, the noisier the measurement. Based on the algorithm and method that is used to estimate the frequency such as Phase Locked Loop, Fast Fourier transformation, zero crossing of sinusoidal measurements and synchrophasor estimation of derivation of angle, harmonics and asymmetry of the voltage signal that is used to estimate the frequency may have more or less influence on the measurement. Therefore, each algorithm and method may have its own sweet spot for time delay and accuracy, which leads to varying requirements regarding filtering methods. The technical report [7] reflects this by a lack of recommendation for classical filtering by low-pass filters, also since stabilization measures such as elimination of single measurement samples may lead to a better outcome for the different methods of frequency measurement mentioned above.

The activation of highly-dynamic frequency reserves such as synthetic inertia, which uses the rate of change of frequency (RoCoF) as input signal, have even higher demands on the frequency measurement since the RoCoF is a derived value of the measured frequency.

Measurement errors in the frequency may lead to a more severe error in the RoCoF since in the simplest case the RoCoF is calculated based on two consecutive frequency samples whose individual error may add up in the calculation of a corresponding RoCoF sample. Since the effectiveness of synthetic inertia decreases dramatically with an increasing time delay of its activation, as described in [8], the time delay of the underlying frequency measurement has to be as short as possible, which leads to an inevitably low accuracy of the frequency samples as well as the RoCoF samples. The technical report [7] approaches this problem by recommending a corresponding low-pass filter depending on the use of the frequency measurement. While synthetic inertia will need a fast measurement, other applications require a much slower measurement with corresponding higher accuracy.

Since the frequency measurement is based on the evaluation of the power system voltage, ENTSO-E [7] recommends at least the evaluation of a few cycles for frequency computation, typically 90 ms – 120 ms. Traditionally, protection equipment requires fast but less precise frequency measurement, while applications for system control require more precise frequency measurement, leading to a slower reporting rate. According to the technical report of ENTSO-E [7] a typical selectable range of accuracy is 10 mHz with a measurement window of 100 ms, which should be measured close to busbars with a high short circuit power. For an accurate RoCoF calculation experience of ENTSO-E [7] has shown that a sliding window over approximately five consecutive measurements gives robust results.

In addition to the above considerations, a series of simulations have been carried out to assess the impact of the different parameters on the effectiveness of the frequency-control-services in case of a reference incident. An excerpt of these simulations has been presented in [4]. A more detailed view on the impact of the frequency measurement time for a scenario according to the classical design hypothesis with an adapted time constant of 6 s is shown in Figure 14. As presented in Figure 14 the impact of the frequency measurement time on the effectiveness of the frequency-control-services is negligible. Consequently, the considerations presented in [7] can also be applied for these frequency-control-services and a frequency measurement time of 500 ms seems appropriate.

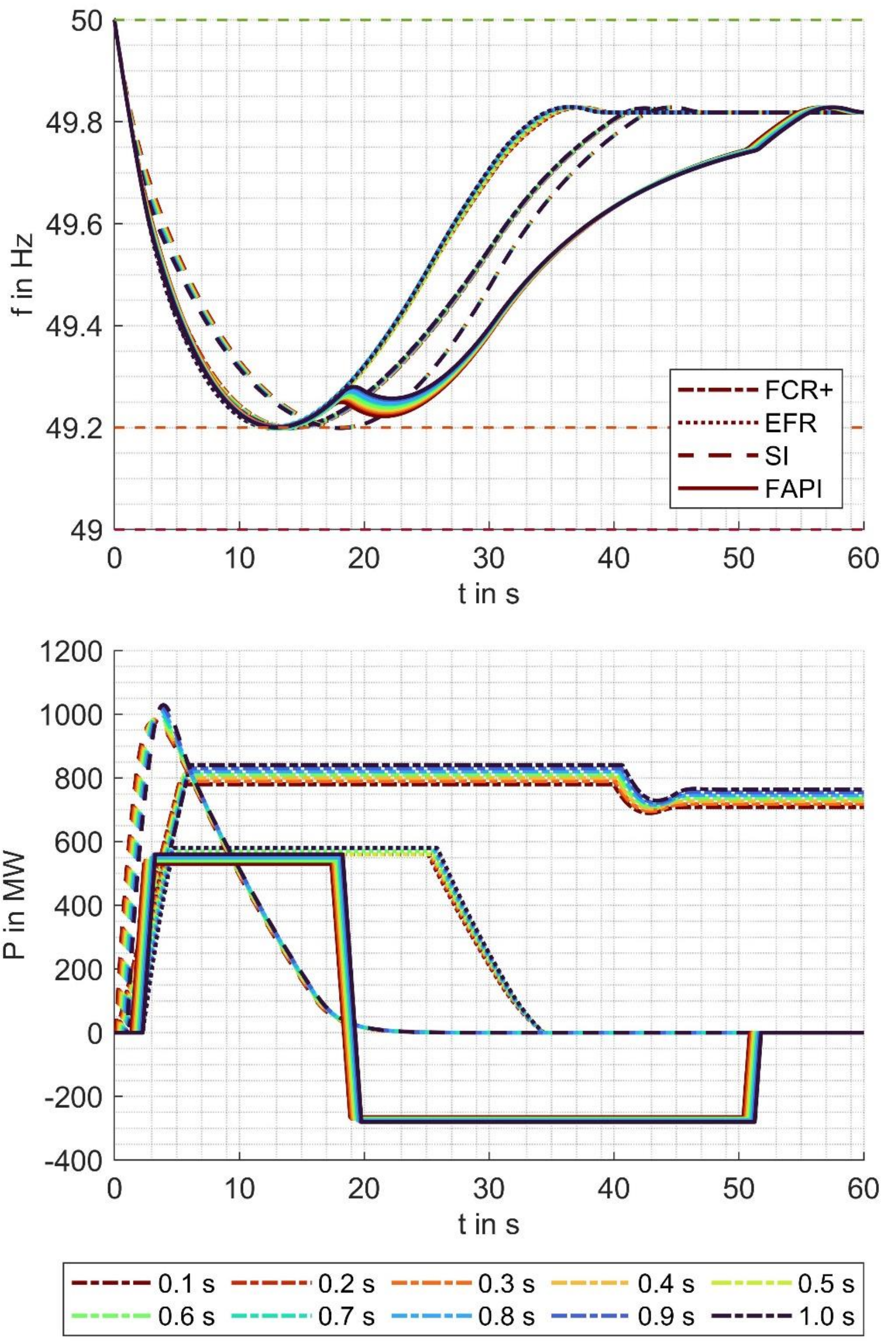


Figure 14: Impact of the frequency measurement time on the effectiveness of the investigated frequency-control-services

5.6.2 Dampening of (low frequency) oscillations

Small signal stability [9] refers to the ability of an electric power system to maintain synchronism after being subjected to small disturbances. When considering the interconnected area, some of the synchronous generators can lose synchronization if a load disturbance occurs. The faster synchronous generator picks up more power in comparison to the other generators. The disturbance can cause insufficient damping of oscillations, which is related to the rotor speed deviation. One main small signal stability issue is insufficient damping, which leads to undamped oscillation in power system. Power system stabilizer (PSS) is a control system that can positively contribute to damping inter-area oscillations. The performance of the PSS implemented in a battery system is investigated in a modified power system model based on the Kundur's two-area system. The power system includes two interconnected areas, each of which has two 900 MVA synchronous machines (SM). All the synchronous machines are equipped with PSS. The battery (400 MVA) is connected to the busbar B1 near SM 2. At t = 160s, a 700 MW load increase occurs at the busbar B2 near SM 4. The interconnected power system model is presented in Figure 15.

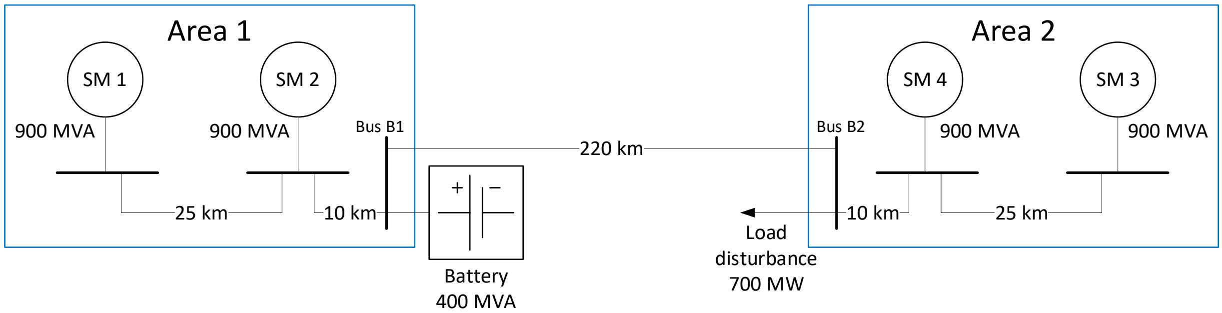


Figure 15: Single-line diagram of the power system model

In order to find out the impact of measurement delay on the PSS performance, dynamic simulations with different frequency and active power measurement delay periods are carried out. The pole-zero diagram provides a qualitative insight into the response characteristics of a system. Therefore, the influence of measurement delay is evaluated based on the change of the location of poles. Figure 16 shows the pole-zero diagram of the inter-area oscillations in case of different frequency and power measurement delays.

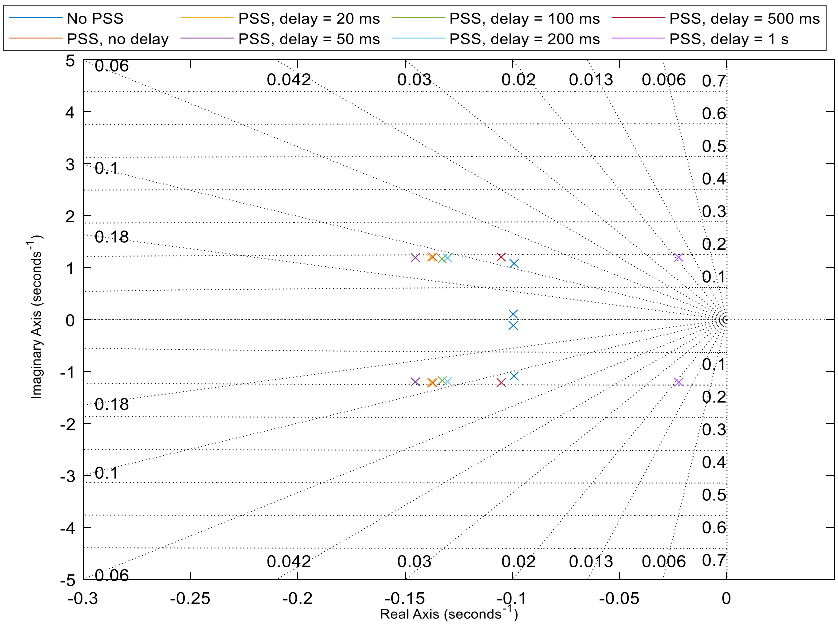


Figure 16: Pole-zero diagram of inter-area oscillations for different measurement delays (oscillations checked from 161 to 180 s)[8]

As can be seen, regardless of whether PSS is activated in the battery converter or not, the system is stable under the load disturbance of 700 MW, because all the poles are found in the left half plane. The negative value of the real part stands for damped oscillations and indicates a steady state. The bigger the absolute value of the real part of the pole is (farther to the left), the faster the dynamic response component decays, so the system is more stable. The frequency of oscillation is determined by the imaginary part of the poles. When adding PSS to the battery system, different system behaviors are obtained, because the poles of a system that implements PSS are clearly shifted compared to a system without a battery PSS. In general, when the measurement delay gets longer, the poles are shifted more to the right. This means a reduction in the system stability. The poles of the inter-area oscillations having PSS with measurement delays below 200 ms are located close to each other, as shown in Figure 16. This indicates that the frequency and power measurement delays shorter than 200 ms do not have a significant influence on the performance of the PSS. The 500 ms measurement delay of the PSS input signal results in the inter-area oscillations similar to that of the system when the battery PSS is not activated. For a delay of 1 s, the poles are close to the imaginary axis. Following this trend, if the measurement delay becomes even larger, the system would no longer be stable and its poles would enter the right half plane.

In addition, the effects of PSS applied to the battery of different capacities are compared, while measurement delay is assumed zero. Figure 17 presents the pole-zero diagram of the inter-area oscillations under different installed capacities of the battery.

---

[8] The x-axis is zoomed in. All the cases have two pairs of poles (high-order system). The non-dominant poles, whose distances to the imaginary axis are five times larger than that of the dominant poles, are not shown. Dynamic simulation results between 161 s and 180 s are chosen for pole-zero diagram, because the amount of data points that can be processed is limited and the system oscillations caused by the load disturbance are considered to be the most representative in this time period.

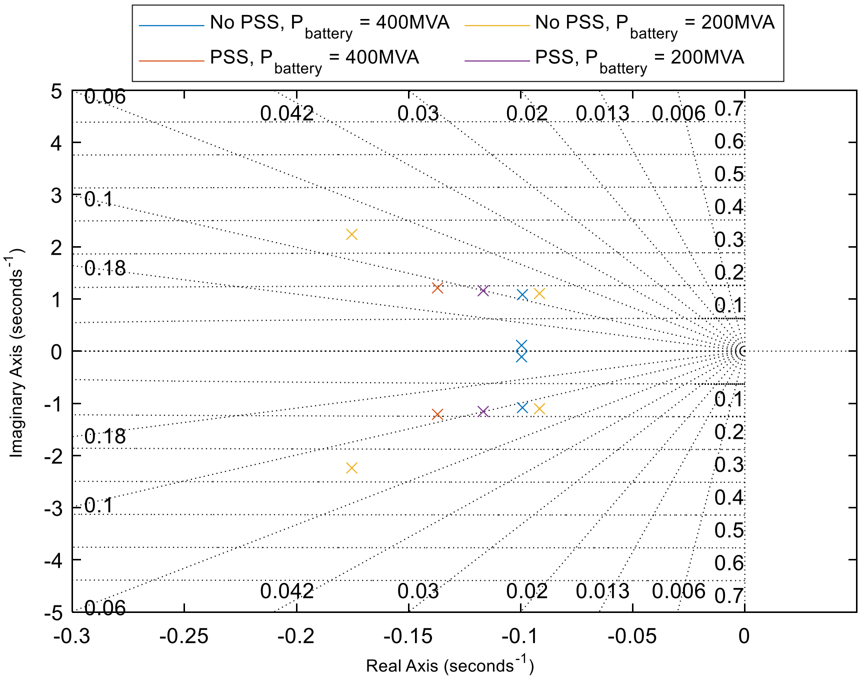


Figure 17: Pole-zero diagram of inter-area oscillations under different battery capacities (oscillations checked from 161 to 180 s)

As shown in Figure 17, under a load disturbance of 700 MW, the power system with both installed capacities of 200 MW and 400 MW of battery storage can be operated stably. A shift is observed by comparing the cases with and without PSS. There is also a difference in the system dynamic behavior caused by the battery capacity. The larger the battery capacity that provides the PSS to dampen the oscillations, the more stable the system.

5.6.3 Repowering the system after disturbances

The Requirements for Generators (RfG) [10] define requirements for all power generating modules, including converter-based modules, termed as power-park modules. Regarding post-fault active power recovery, the RfG defines in Article 13(7) the general requirement for all power-generating modules to be capable of connecting automatically to the network, for which the relevant TSO can specify the corresponding conditions within which such an automatic connection shall be possible. Besides the general fault-ride-through requirement for power generating modules of type B - D, this requirement guarantees that all modules are capable of reconnecting to the network after a long-lasting fault, beyond the required duration of fault-ride-through capabilities of power generating modules. Article 20(3) defines detailed requirements for the post-fault active power behaviour of power park modules of type B – D. Article 20(3a) states that the relevant TSO specifies when the post-fault active power recovery begins, based on a voltage criterion, the maximum allowed time for active power recovery, and a magnitude as well as accuracy for active power recovery. According to Article 20(3b), these TSO specifications shall respect the principles of the interdependency between fast fault current requirements and active power recovery, the dependence between active power recovery times and duration of voltage deviations, a specified limit of the maximum allowed time for active power recovery, the adequacy between the level of voltage recovery and the minimum magnitude for active power recovery, as well as the adequate damping of active power oscillations.

Corresponding national requirements regarding post-fault active power recovery in Austria are defined in the TOR Erzeuger type A – D [11], subsection 5.2.2.2. The TOR requires power generating modules to increase their active power injection after a fault in the network to restore to pre-fault values as fast as possible.

5.6.4 Deterministic Frequency Deviations (DFDs)

DFDs describe the frequency events around the full (and to a lesser degree quarter) hours, caused by the decoupling of production and load resulting in deterministic power imbalances and frequency excursions. Figure 18 illustrates this effect.
While the load-curve follows a continuous course over the day, the production of energy is based on the block-formed power plant schedules. This leads to significant power imbalances around the full hours, when the schedule changes, resulting in frequency excursion of up to ±100-200 mHz [12].

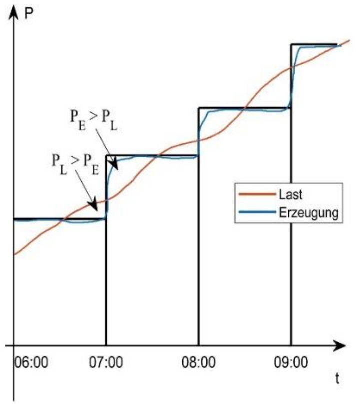
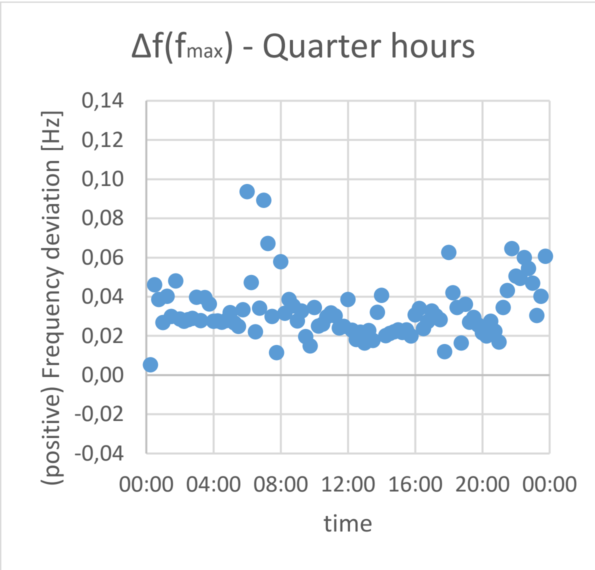


Figure 18: Cause of DFDs

In order to develop a frequency-control-service against DFDs, the real frequency data needs to be analyzed. Figure 19 to Figure 21 show the frequency maxima and minima as well as the time distribution of the maximal frequency deviation during the day for a selected day (07.08.2018).

Frequency maxima (07.08.2018)



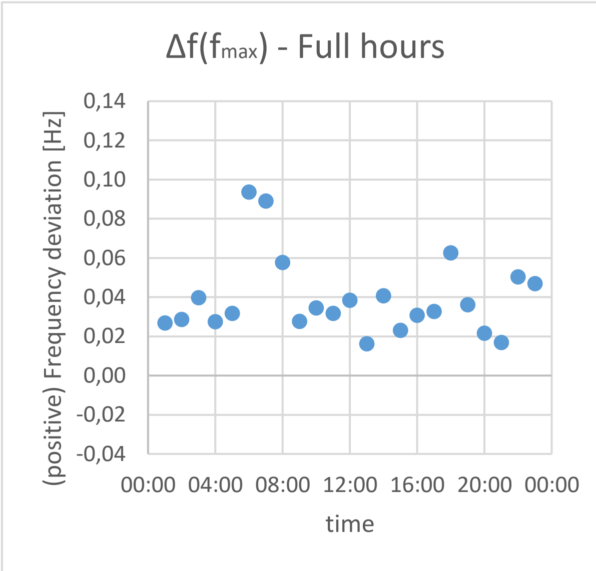
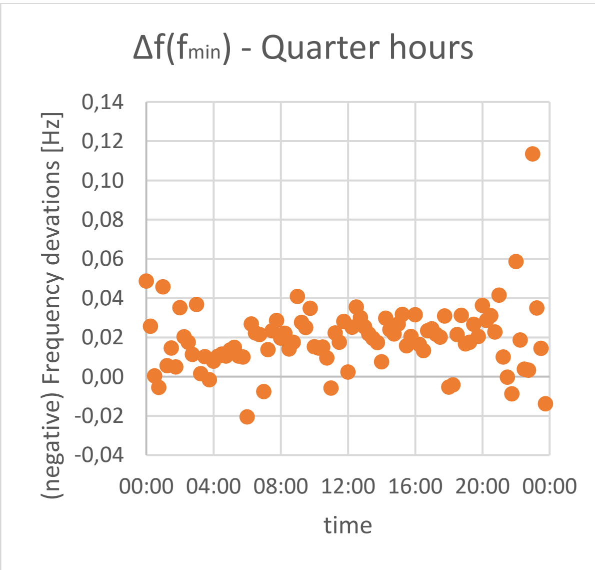


Figure 19: FREQUENCY- maxima during the day

Frequency minima (07.08.2018)



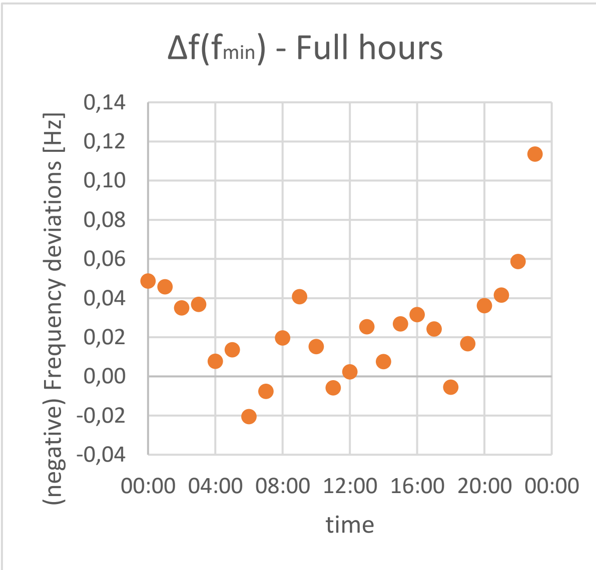


Figure 20: FREQUENCY- minima during the day

Time distribtuion of the maximal frequency deviation (07.08.2018)

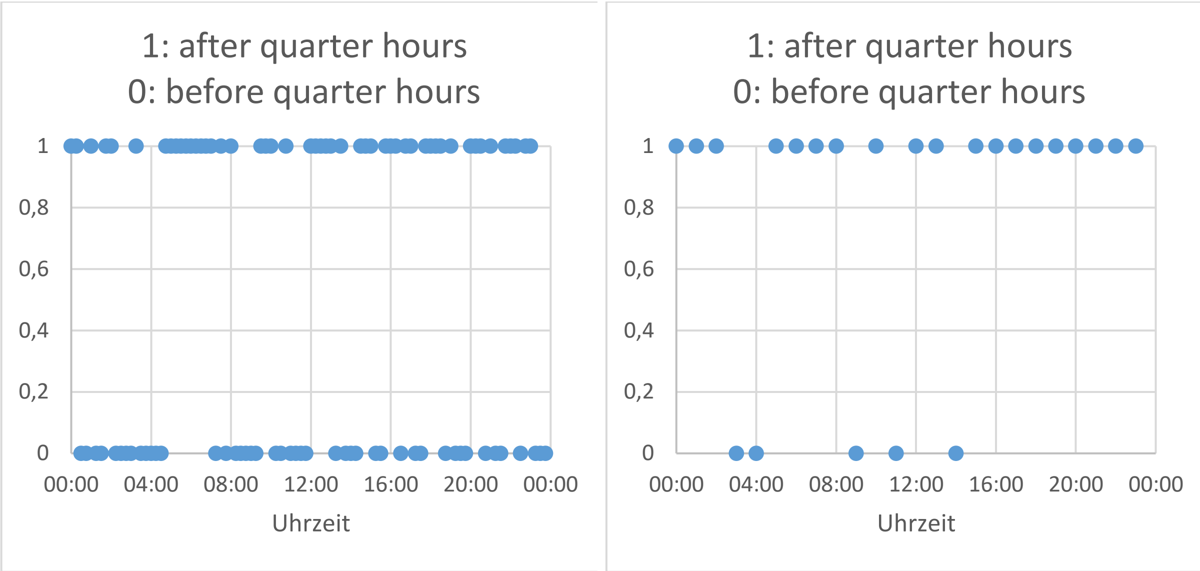


Figure 21: Time distribution of maximal frequency deviations

The figures above illustrate, that the frequency deviations can reach values above 100 mHz and that the biggest frequency excursions happen around the full hours. Figure 21 also shows, that while there is no significant pattern regarding the time distribution around the quarter hours, there is a recognizable pattern for the full hours. Most of the large frequency deviations occur after the full hours within a range of around 5-10 Minutes. This means that a frequency-control-service aimed at limiting DFDs would have to operate mainly in a window ±5 Minutes around or 5 Minutes before and 10 Minutes after the full hours.

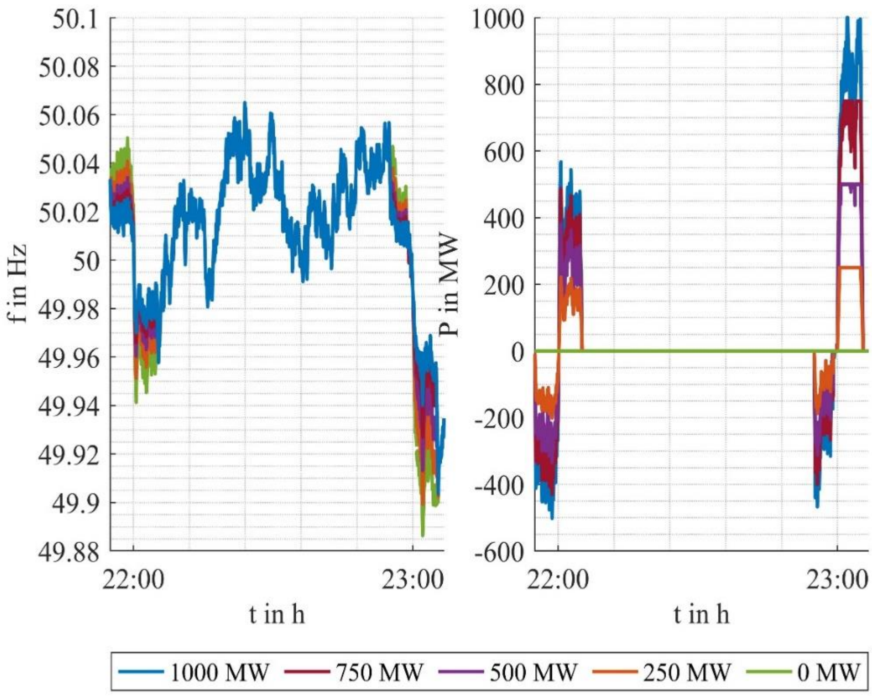


Figure 22: Effect of a frequency-control-service against DFDs

The investigated frequency-control-service against DFDs is designed with the same frequency- and time-characteristic curves as FCR but it only operates within the said periods. The exemplary effect a frequency-control-service against DFDs could have had on the frequency on the 07.08.2018 is depicted in Figure 22. As the figure illustrates, the frequency deviations could have been reduced effectively by introducing such a frequency-control-service, therefore setting free FCR and improving frequency stability. Nevertheless, the adjustment of the regulatory framework to counteract DFDs via changes in the deduction of the imbalance settlement period or the introduction of ramp-based power plant schedules (opposed to the current block shaped schedules).

5.6.5 Frequency stabilization following a blackout

Power System Restoration (PSR) is critical to bring the system back to normal operation condition following an outage or a blackout. Long-lasting power interruptions in voltage grids may cause an initial peak value of active power of load demand being much higher than its previous value, which is known as cold load pickup (CLPU).

As reported in [13], the CLPU is a phenomenon caused mainly by the loss of diversification among groups of thermostatic controlled loads (TCL) such as heat pumps, fridges, freezers, and boilers. The effect is seen on the active power peak value of a group of TCLs connecting to a network transformer at the instant of the re-energization, which can reach a value up to 2-3 times of the one in normal operation by neglecting the fast transient process. The CLPU behavior considered in the simulations and dynamic frequency characteristic of load re-connection are depicted in Figure 23. As typical values found in this study, the factor $K_{CLPU} = 2.5$ and $T_{CLPU} = 600\ s$ have been chosen. The dashed line is the CLPU behaviour, a time depending factor used to multiply the steady state power consumption during cold load pick up and the solid line shows the simulated dynamic frequency response following a load re-connection. The frequency response after load re-connection is most critical in the first phase of the system restoration, as only little inertia is in the system and the system frequency is more likely to collapse again.

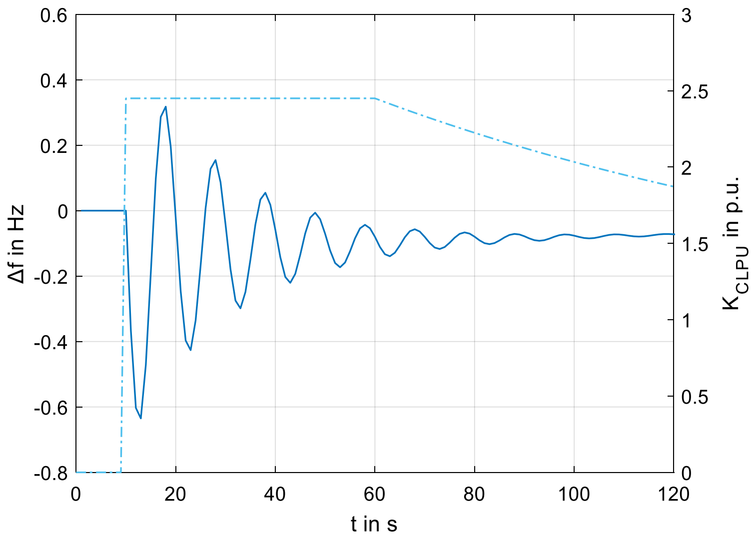


Figure 23: Frequency response of the system after load connection [13]

The PSR models represent residential loads with the mentioned CLPU effect, PV converters with their synchronization and start-up behaviors, battery energy storage systems (BESS). The BESS is assumed to have its own power converter independent of the PV-inverter with no synchronization time requirement and no black start capability. It has a self-discharging behavior during the power interruption and can cover the CLPU power peak fully or partially at the instant of re-energization depending on the power level and the state of charge (SoC) at that moment.

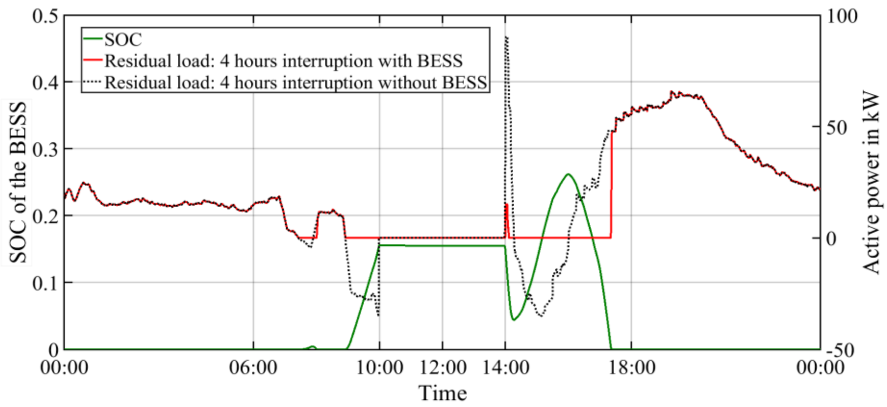


Figure 24: PSR model aggregation for a 4-hour power interruption with BESS details [14]

An aggregation of all abovementioned models for an outage duration of 4 hours in a working day in the summer of 2022 is illustrated in Figure 24. The aggregation consists of a network group with 100 households each having an average installed PV capacity of 1.5 kW and a respective BESS. The aggregated BESS for the whole network group has 150 kWh storage capacity with a 75 kW loading power.

The BESS starts with SoC zero as shown with the green solid line. The charging and discharging processes of the BESS are based on the residual load profile shown with the black dotted line. This curve represents the model aggregation without the BESS. The BESS gets mainly charged at around 9:00 as the residual load has a negative value. When the power interruption starts at 10:00, the residual power becomes zero and the BESS starts to discharge due to its self-discharging effect. By the re-energization at 14:00, the battery kicks in immediately covering a big part of the residual load. The BESS discharging power is limited and lower than the residual load power at the instant of the re-energization. Therefore, it cannot fully cover the residual load. The remaining residual load power has to be supplied from the external grid. It is observable by the power spike at 14:00 in the residual load with a red solid line. As the PV generators kick-in a few minutes after the re-energization time instant, the residual load becomes negative again and the BESS gets charged once more. The BESS gets fully discharged at around 17:00 and the red solid line returns to the residual load curve. The BESS is practically involved in the PSR from the beginning of the re-energization for a duration of 3 hours. This results in an almost zero residual load in this interval, which is seen from the external grid [13].

The aggregations of the models for different outage durations without the BESS are plotted Figure 25. The black line indicates the residual power in normal operation, while the colored curves are ones with interruptions at 10:00 with interruption durations from 1 to 10 hours. Apparently, "ping-pong" effects are observable, which are caused by the CLPUs and the belated PV inverter re-synchronizations.

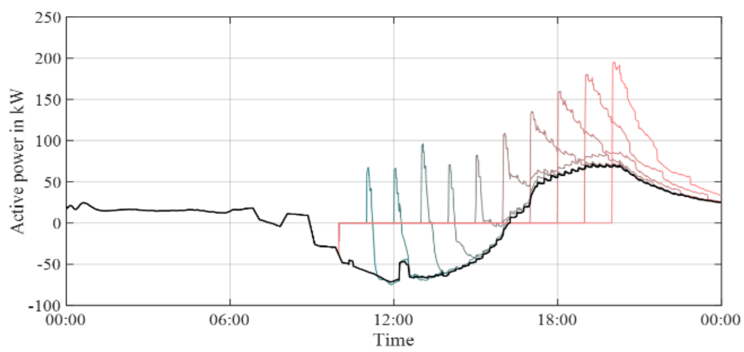


Figure 25: PSR model aggregation for a 4-hour power interruption without BESS details [14].

To overcome the deficiency or surplus of generation during load pickup, BESS can be used to compensate the imbalance and expedite the load pickup process [15].

5.7 Simultaneous provision of different functions

Due to the still relatively high costs of battery cells, BESS projects often struggle to reach profitability today. On the one hand, this situation stems from the lack of market options, with which BESS get properly remunerated for their unique strengths among all technical entities available. On the other hand, the use of BESS often is limited to the provision of an individual service. IRENA's Electricity Storage Valuation Framework [16] lists several policy incentives to support cost-effective storage deployment, which include the creation of new markets such as for the provision of highly dynamic frequency response products. Until such new markets are established, but also beyond that, the stacking of services is considered a crucial issue in order to reach profitability or a more cost-effective operation of BESS since it allows capturing higher revenue streams [16, 17]. Especially in the short-term and medium-term, when the costs of BESS continue to fall, such an operation can be important to compete in a challenging environment. Numerous studies have used data from electricity markets confirming that investing in storage systems providing a single service only often does not pay off. However, when storage systems provide additional services, for example, a variety of system services in parallel, and these services are monetized, then profits are notably improved [18-23].

According to Englberger et al. [24] there are three options to stack services, which are displayed and compared in Figure 26 based on the example of three different services.

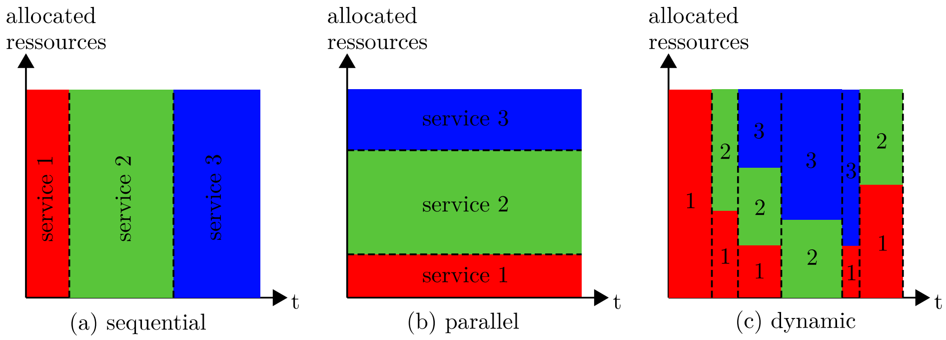


Figure 26: Options of stacking three services

A sequential stacked operation is defined as an operation in which one service uses all resources of the BESS for a given time, after which another service takes over, etc. A parallel stacked operation is defined as an operation in which the resources of the BESS are divided in a predefined proportion between different services that are active at the same time. Shares of each resource can be viewed as “virtual” BESS, which provides a corresponding service and when put together form the real BESS. A dynamic stacked operation is similar to the parallel operation, but dynamically allocates the share of resources for different time slots. The constraints are growing with the type of stacking, which are few with a sequential stacked operation and increase when using a parallel or even a dynamic stacked operation. These constraints result from the limited power and energy resources of a BESS. Assuming a dynamic stacked operation, a certain number of virtual BESS can be assigned to each time slot, each assigned to a certain service.

The auction frequency and tendered products for services regarding frequency control have already been shortened in recent years and are expected to further approach in the direction of real time markets. Expecting several new products of highly dynamic services for frequency control to get market-ready in the near future, this opens up the possibility for BESS to optimize their operation and revenue streams by stacking such services sequentially, parallel or dynamically.

For the example of a sequential stacking of services, such an optimization may be illustrated by assuming volatile prices for products throughout the tendered time slices of the day. This may result in offering different services in each time slice throughout the day to optimize revenue streams. By considering constraints such as the necessary management of the state of energy of a BESS, a changing provision of services may open up the possibility to optimize the operation together with the corresponding revenues.

Taking into account the specification of FCR+ (5.4.1) and EFR (5.4.2) a parallel stacking of these two exemplary functions may be achieved since the corresponding activation windows and hence power outputs of each product can be distinguished easily.

Depending on the actual design of a product SI, as it is described in Section 5.4 for different design principles, certain difficulties may arise when it is stacked with other highly dynamic products for frequency response, especially regarding the resulting time behavior of stacked products. For example, the inertial response of synchronous machines following a frequency deviation in the grid is coupled with a recovery period during which the sign of the power output is opposite to the sign of the current frequency deviation, which is caused by the change of the sign of the RoCoF during stabilization of the frequency after a frequency event. However, especially in stacked operation with other highly dynamic products for frequency response, such a behavior that is mimicked in the design of SI may diminish the contribution of such highly dynamic products during the recovery period of SI due to opposite signs of power outputs of the stacked services. A design of SI that relies on the zone-selective activation of SI, as for example described in Chapter 4, can be a solution to overcome this issue. Besides such issues with the time behavior of the power output of stacked products, basically little speaks against stacking SI with other highly dynamic services for frequency response, as far as they can be distinguished by corresponding allocations of virtual BESS, which guarantee a defined amount of power and energy resources that is allocated to the services.

5.8 Technology potential analysis

This chapter supplements the considerations presented in subsection 7.2.3 of WP6 regarding the suitability of different technologies for providing fast frequency responses. Particularly, relevant values for the ramp rates as well as the capacity for the different technology options are given to elaborate the results presented in section 4.3. An overview of the ramp rates of the different technology options are given in Table 5.

Table 5: Ramp rates of different technology options [33-35]

Technology option	Ramp rates [%/min]
Nuclear	0
Coal	1-6
Combined Cycle	2-8
Gas	8-15
Run-of-River	100
Pumped storage	100
Renewables (Wind, Solar)	>>100
Energy storage (Battery, Flywheel, Supercaps)	>>100

As presented in Table 5, thermal power plants show relatively low ramp rates. Furthermore, these ramp rates are not constant, but rather slow at the beginning and the end of the ramping process and therefore only serve as an average ramp rate. For base-load power plants (e.g. nuclear), the ramp rates are assumed as 0, since these power plants are not supposed to change their operating point within short time frames. Run-of-River and pumped storage plants on the other hand show sizable ramp rates. However, these ramp rates only apply during operation and cannot be guaranteed from a standby state. Additionally, frequent and fast ramp rates can lead to an increased wear of mechanical components and should therefore be avoided. Finally, renewable energy sources and energy storage options connected via so-called power park modules show very fast ramp rates of nearly 100% change in power within seconds.

Table 6 presents an overview of the possible duration for which, different energy storage options could provide frequency-control-services. For thermal, run-of-river and pumped storage power plants, it is assumed that they could provide frequency-control-services for very long periods or indefinitely. Furthermore, heat, hydrogen and gas storages are not considered in Table 6. While these storages could provide energy from a few hours up to weeks or even months, they require the same processes as thermal power plants to convert the stored energy and therefore lack the necessary ramp rates.

Table 6: Possible duration of provision of frequency-control-services for different energy storage technologies [36]

Technology option	Duration of provision
Flywheel	From seconds up to a few minutes
Supercapacitor	From seconds up to a few minutes
Battery storage	Few hours

Regarding the availability of power and the ability to ensure provision of the frequency-control-services, all technology options except for renewable energy sources meet the necessary requirements.

A summary of these results as well as additional aspects of the technology potential analysis are presented in Chapter 8.

5.9 Conclusions

The first chapters of the WP2 and WP3 introduce the goals of the WPs as well as the investigated scenarios and frequency events. The selected frequency events determine the necessary models and approach needed for the simulations. In addition to the base single-area-model, these include different variations considering additional areas as well as a closed-loop implementation of the original model. The scenarios and system parameters on the other hand define the resulting frequency gradients and dynamic frequency deviations, which serve as a reference for the design of appropriate frequency-control-services. Within the scope of this project, four different frequency-control-services are investigated. These are the Frequency Containment Reserve+ (FCR+), Enhanced Frequency Response (EFR), Synthetic Inertia (SI) and Fast Active Power Injection (FAPI). The detailed specifications of these services including their frequency- and time-characteristic curves as well as their parametrization are presented in section 5.4. Section 5.5 shows an excerpt of the corresponding results of the necessary demand as well as the suitability of these frequency-control-services for a system level deployment in the RGCE. These results show that FCR+, EFR and SI provide a positive impact on frequency quality and offer good scalability and are therefore well suited for a system level deployment in the RGCE. FAPI on the other hand is not suited for use on a system level, even though it can provide benefits for frequency stability in certain cases. Following, section 5.6 gives an overview of several aspects regarding the simulation-based development of functions, such as frequency measurement, DFDs or low-frequency oscillations. Additionally, in section 5.7, the simultaneous provision of different functions is considered and corresponding aspects for their design are derived based on existing products in the synchronous area United Kingdom. Section 5.8 shows certain supplementary technical aspects regarding the technology potential analysis conducted in subsection 8.2.3 of WP6.

6 Laboratory tests

6.1 Introduction

This chapter summarizes the laboratory and controller hardware-in-the-loop tests that have been performed on the storage system, with special emphasis in inverter functionality and battery management. Before its final commissioning in the field, the control algorithms were first being tested in a laboratory setting. Complementary to these lab tests, the controller Hardware-in-the-loop (c-HIL) tests ran in parallel to help with the function definition and to shed some light into the results obtained in the laboratory.

The device under test consists of one a storage system of 1 MW and 500 kWh, to be deployed at a later stage at an Austrian Power Grid (APG) substation close to Vienna. The system corresponds of a storage unit, two three-phase, 4-quadrant DC/AC inverters equipped with LCL output filters. The DC voltage level on the battery ranges from 700V to 1000V (depending on the state of charge, SoC), while the control boards, DAQ system, RTS and interface boards AC voltage magnitude is 400V.

6.2 Preliminary Controller Hardware-in-the-loop tests

The objective of the C-HIL tests is twofold:

a) Validation of the controller functionality with comprehensive tests in order to characterise the behaviour of the system in details under fully controller conditions (e.g. impact of disturbances, impact of different control-settings). The main purpose of these tests is to fully characterise the storage system not only under normal conditions but also in tests which are not possible or hard to implement in the field. This detailed characterisation might allow to identify limitations on the actual operation area, limitations on the parametrization (e.g., shortest achievable response time guaranteeing well damped response).
b) Validation of the tests performed in the laboratory (mainly low voltage ride through (LVRT), primary frequency control and virtual inertia). The purpose of these tests is to, first, validate the C-HIL set-up including the interfaces and parametrization on the basis of well documented tests before performing more comprehensive tests; and second, be able to characterize the behaviour of the system in a controlled environment and under a wider range of parameter setup and excitations.

The C-HIL setup consists of two main parts. The first part is the controller of the battery energy storage system (BESS). The second part represents the power hardware of the BESS as well as the local grid the BESS is connected to. In this case this is the laboratory grid or the field trial site grid. The setup is adjusted from case to case especially for the validation of laboratory and field tests. Out of four converters and battery systems two are modelled and implemented in the C-HIL setup. A simple battery emulator is used. There are 2 main controllers of the system that are relevant for these C-HIL tests, namely the low level inverter controller, and the high level local controller that behaves like an Energy Management System (EMS).

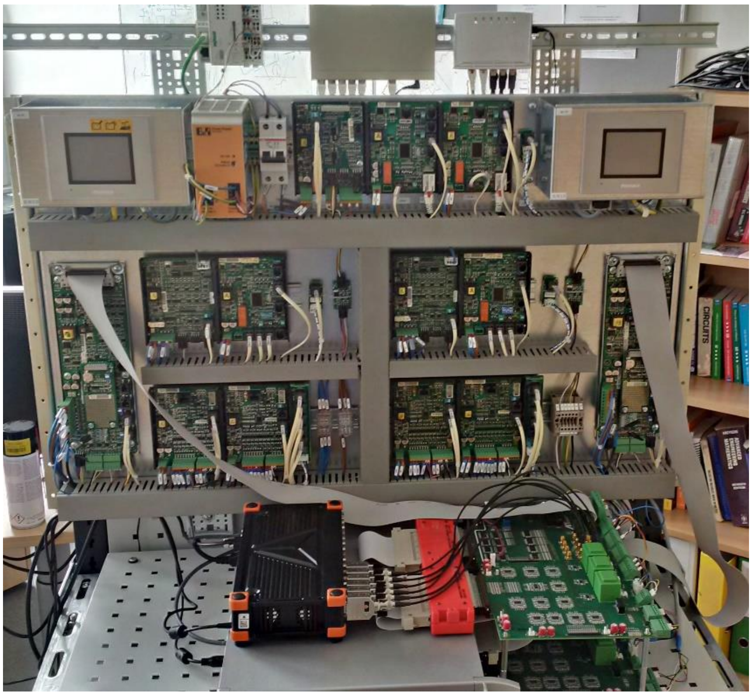


Figure 27: C-HiL Setup with real-time simulator and control cards

Many tests were carried out with the c-HIL setup in an automated way, to prove the correct behaviour of the unit and to explore the impact of several parameters. We provide here a short snapshot of the most relevant tests for brevity reasons, focusing on the verification of the EFR function.

The power being delivered by standard EFR can be roughly described as being proportional to the frequency deviation with respect to a give nominal frequency. Notice that, while the expression seems to be the same as in standard primary frequency response, the response time is expected to be much faster. In order to evaluate the effect of implementation aspects and possible delays, the function has been slightly modified adding adjustable characteristics, such as deadbands, gains, hysteresis band and activation times. All these characteristics have been implemented in a Simulink model (see Figure 28) in order to validate the expected behaviour from the system (both in HIL and lab setups).

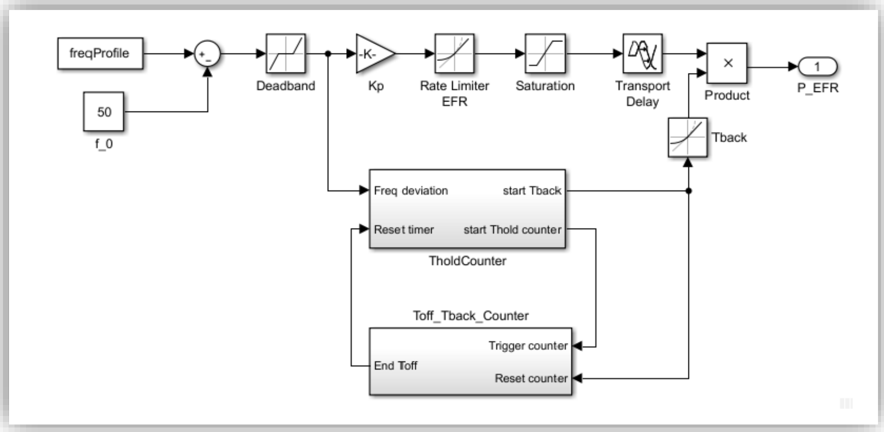


Figure 28: Block description of the EFR function

Likewise, all testing and comparisons have been automatized using scripts in Python (to control the C-HiL setup) and in MatLab (to run the simulations of the ideal model and perform the comparison). Such an automated procedure allows us to explore impacts of the function specification (deadbands, droop, tolerance, hysteresis, etc.) on the requirements of each asset (energy-to-power ratio, dynamic response, etc.)

Figure 29 and Figure 30 shows the system response for a standard large frequency deviation under different values for the droop gain and deadband, respectively. In both cases, we have set Thold = 30s, Tact = 0s and Tback = 10s. The system response is very similar to our expected response (from our simulation model).

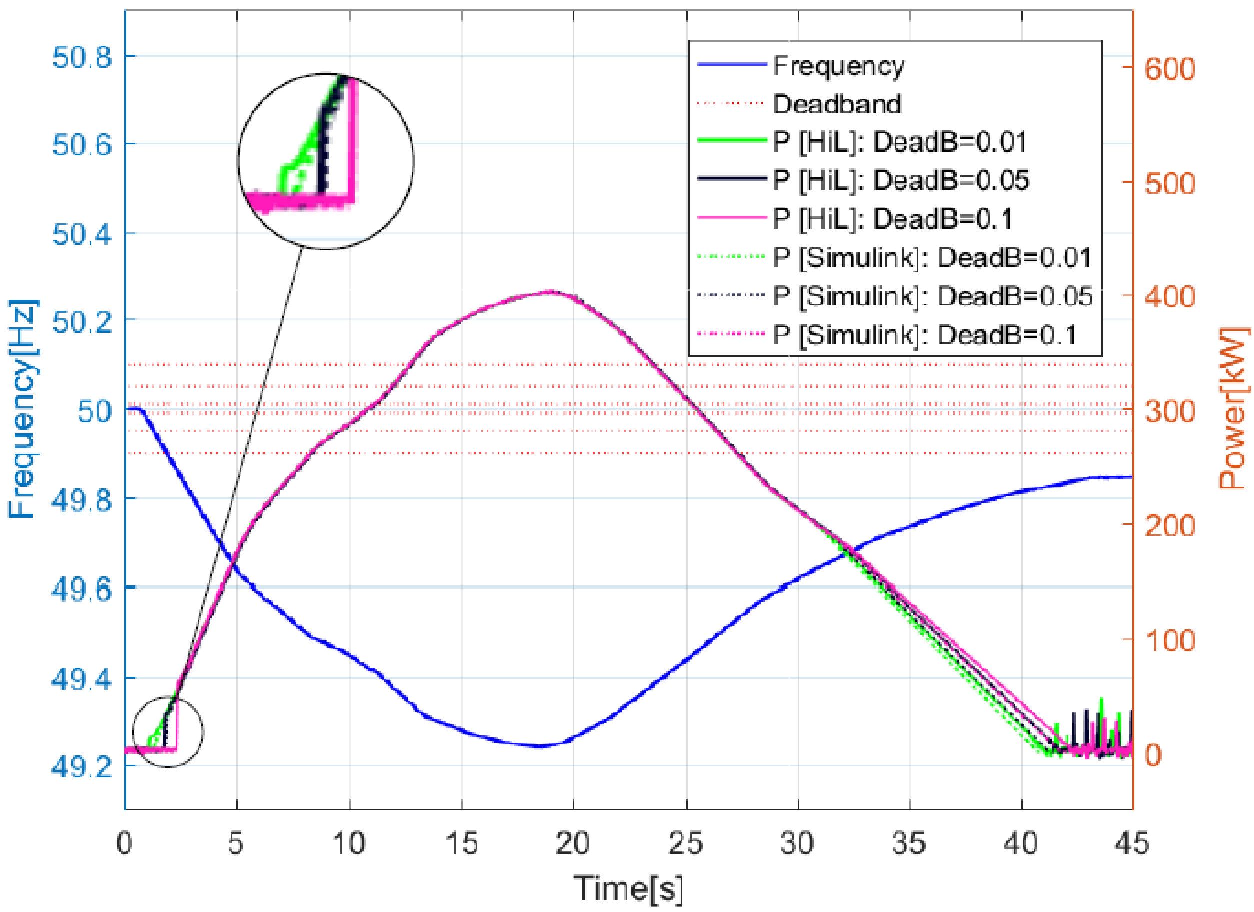


Figure 29: Comparison of system response against expected response for different values of deadband

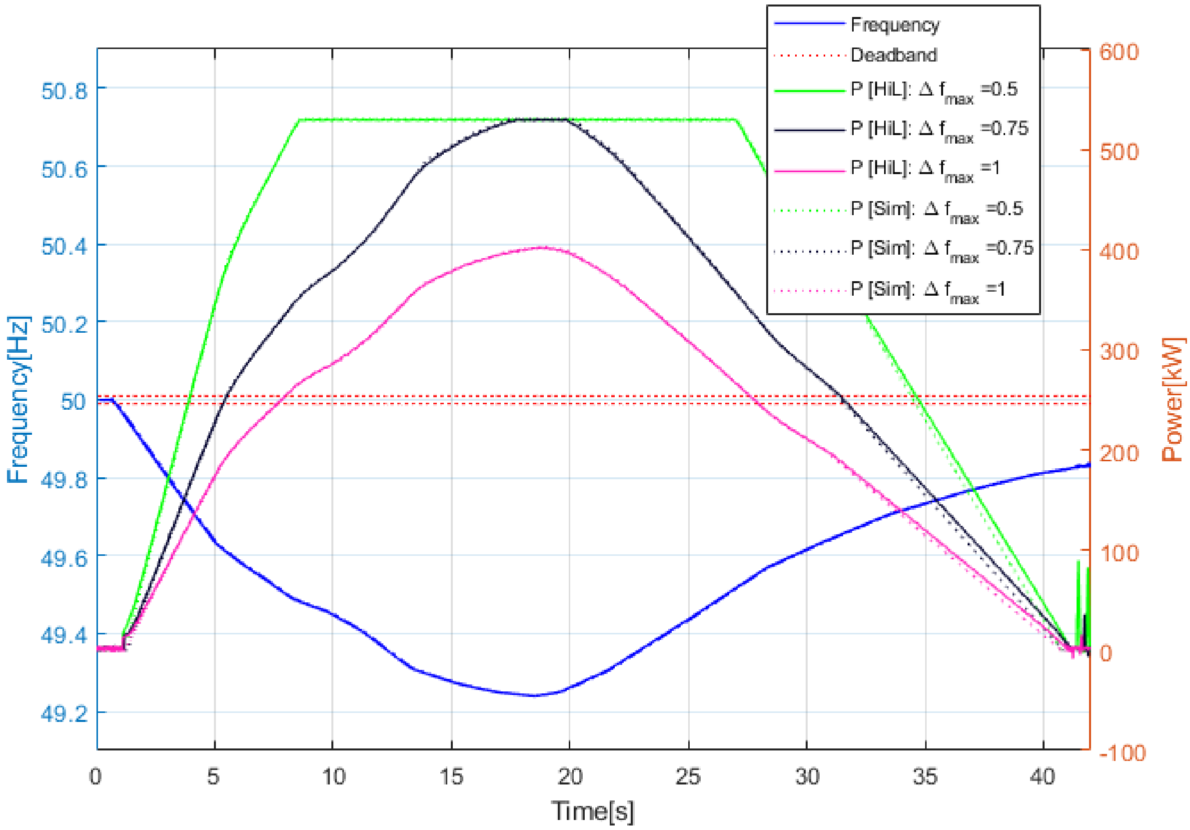


Figure 30: Comparison of system response against expected response for different values of droop gains (Δf_{max})

Similar tests were carried out for synthetic inertia, deterministic frequency deviations, power system stabilizer, etc. After a few iterations, the results from the c-HIL simulations fit with great accuracy the expected response as defined in the specification and replicated via Simulink models. Nonetheless, in the case of synthetic inertia, electrical noise plays such a big role that c-HIL simulations are not very informative and exhaustive lab tests are needed to fully assess the robustness of the function.

6.3 Laboratory setup, test procedure and automatization

In order to properly test all functions in a controlled environment, the storage unit is connected to a grid simulator that is able to reproduce different frequency and voltage profiles. The test environment at the AIT SmartEST High Power Laboratory consists of a three phase AC test grid with an additional isolation transformer and an autotransformer which provides a variable AC voltage according to the specifications of the EUT (equipment under test). For measurement of AC and DC parameters, a PC based measurement and data acquisition (DAQ) system with appropriate current transducers is available at the laboratory. Moreover, to monitor the behaviour of the system a Dewesoft 7and a PMU from Arbiter were employed.

For simplicity and due to constraints in the laboratory setup, all tests were performed at the low voltage level (400V), and with the total power delivered to 500kW. This represents no drawback to fully test the main functionality of the system.

As in the case of the C-HIL environment, the laboratory tests have been automatized with the help of a real-time simulator (RTS). A Typhoon HIL has been connected to a programmable AC source, that defines the voltage and frequency profile at the point of common coupling for the storage unit. The RTS is fully programmable via Python, being able to create different profiles from recorded measurements or synthetic profiles. A library of relevant profiles containing all waveforms that are of interest (synthetic profiles and historical measurements) and used during the test phase in the laboratory was developed. The storage system can also be programmed and configured via Python, making it possible to define in a single script the list of tests, composed of certain profiles and different function parameters that need to be executed. For the analysis part, the measurement system (Dewesoft) is also programmable with MatLab, hence the analysis and visualization can also be automatized. This automatic approach, shown in Figure 31, facilitates test coverage and repeatability, as it allows us to cover many different cases and test the behaviour under various parameter sets.

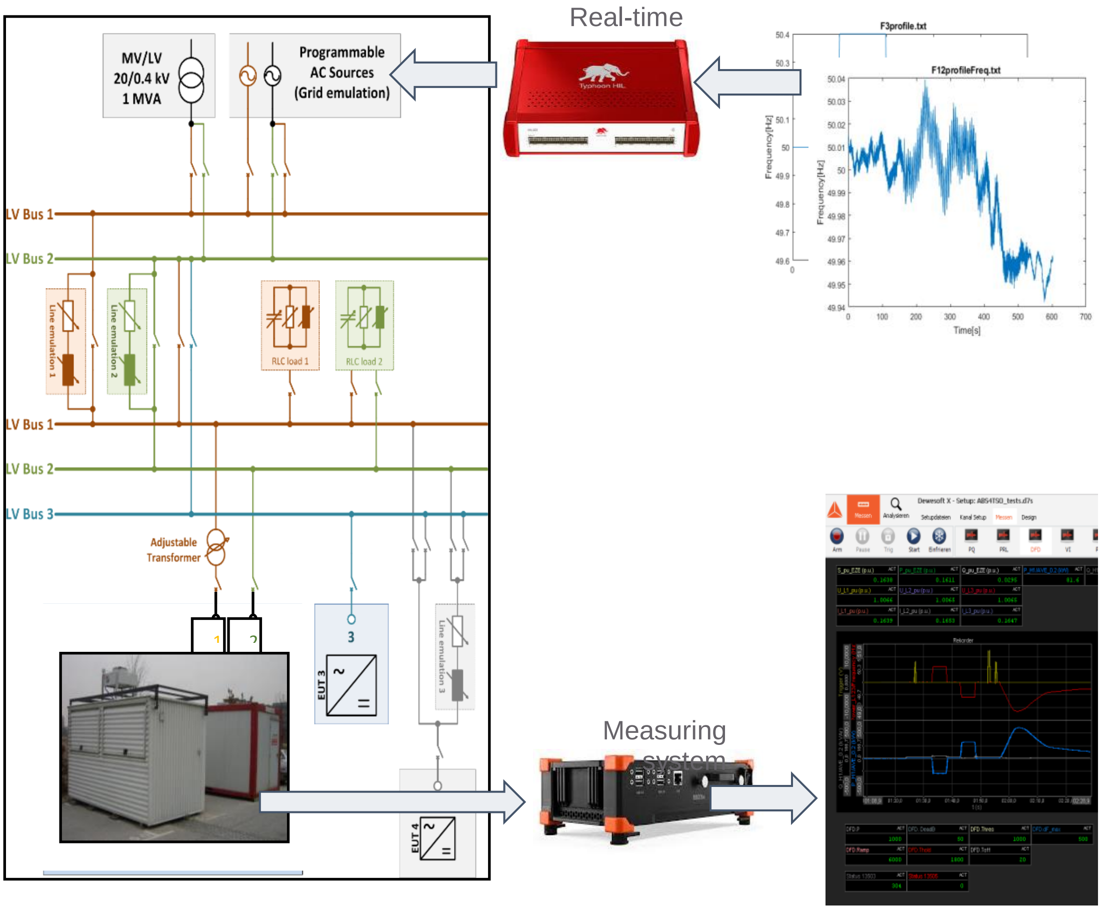


Figure 31: Automatic test procedure for the lab setup

6.4 Laboratory Test results

For compactness, the definition of the functions and their purpose is not detailed here, and we refer the interested reader to (1) for a full characterization. The results of the tests are summarized in Table 7

Table 7: Summary of the lab tests

Function	Requirements satisfied?
Enhanced Frequency Response (EFR)	Yes
Synthetic Inertia (SI)	Yes
Deterministic Frequency Deviations (DFD)	Yes
Power System Stabilizer (PSS)	No – tests were completed using the cHiL setup
Post Fault Active Power Recovery (including LVRT tests)	No – tests were completed using the cHiL setup
Multimodal operation	Yes
PQ diagram	Yes
Efficiency analysis	Yes
Frequency-dependent power reduction	Yes
Time to full power	Yes
Cycling tests	Yes
Cos(phi) Regulator	Yes
Island detection	Yes (unclear though if the implemented functionality would work in the field)
Efficiency cycle	Yes

Regarding the PSS function, preliminary results were unsuccessful. Due to time constraints, further improvements and tests could not be performed, and the function was tested in a c-HIL environment and later on during the field tests.

Among all functions implemented in the system, we focus in this report in those relevant to the main goals of the ABS4TSO project, namely, frequency-related functions targeting grid stability. Other standard functions (e.g., cos(phi) or low-voltage ride through) are important for the correct operation of the storage system but do not bring special insights into the impact of novel ancillary services in future low inertia grids.

6.4.1 Enhanced Frequency Response

During all these tests, only the EFR function is activated, while all other functions are disabled. The response of the system is compared against a Simulink model that implements the specified function. Unless specified, the following parameters will be used.

- P = 500 kW (maximum power the function can deliver)
- Δf_{max} = 1 Hz (frequency at which the maximum power is delivered, defining implicitly the droop gain of the frequency response)
- Δf_{db} = 0.01 Hz (deadband in frequency)
- Thres = 100 % (threshold to implement a hysteresis band)
- Tact = 0s (activation time)
- Tfull = 0s (time to reach full power)
- Thold = 30s (time during which the function is active)
- Tback = 10s (time to ramp down after reaching Thold)
- Toff = 5s (time during which the function is disabled, after ramping down to 0)

The first test performed consists of a simple step-like frequency deviation, which allows us not only to evaluate the behaviour of EFR, but also to measure the reaction time of the system. This reaction time is typically influenced by several factors: PLL reaction time to frequency changes, delays caused by the software, and the physical dynamic response of the battery and the inverter. Figure 32 shows similar behaviour from the system and the ideal simulation model. Nonetheless, the real response in the laboratory depicts a slightly slower starting time compared to the model, and a slower settling time, due to the dynamics of the battery.

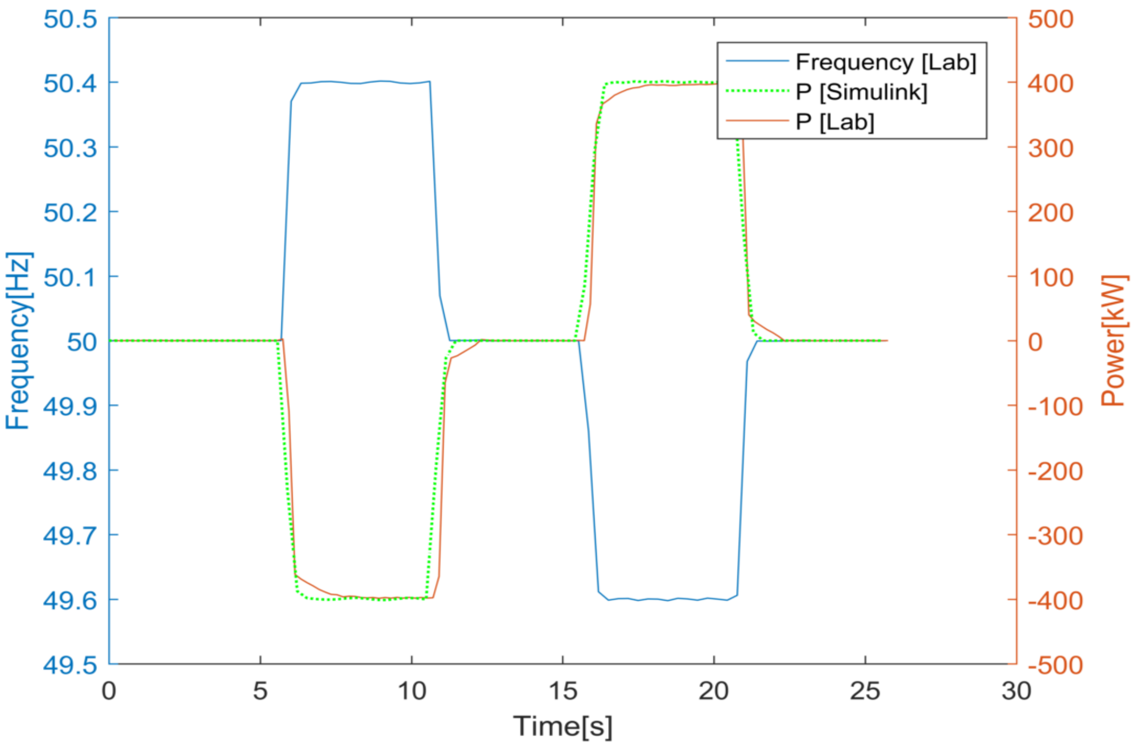


Figure 32: EFR under consecutive frequency steps

Similar results were obtained using standard frequency deviations proposed by ENTSO-E, corresponding to high RoCoF and low RoCoF events. To test the behaviour of the system under continuous, consecutive frequency deviations, a synthetic frequency profile has been created. It is important to realize that every time the power goes back to 0, the counter of *Thold* is reset to 0. Therefore, for this frequency profile the function is always active. Also in this case the expected response and the measured active power are similar.

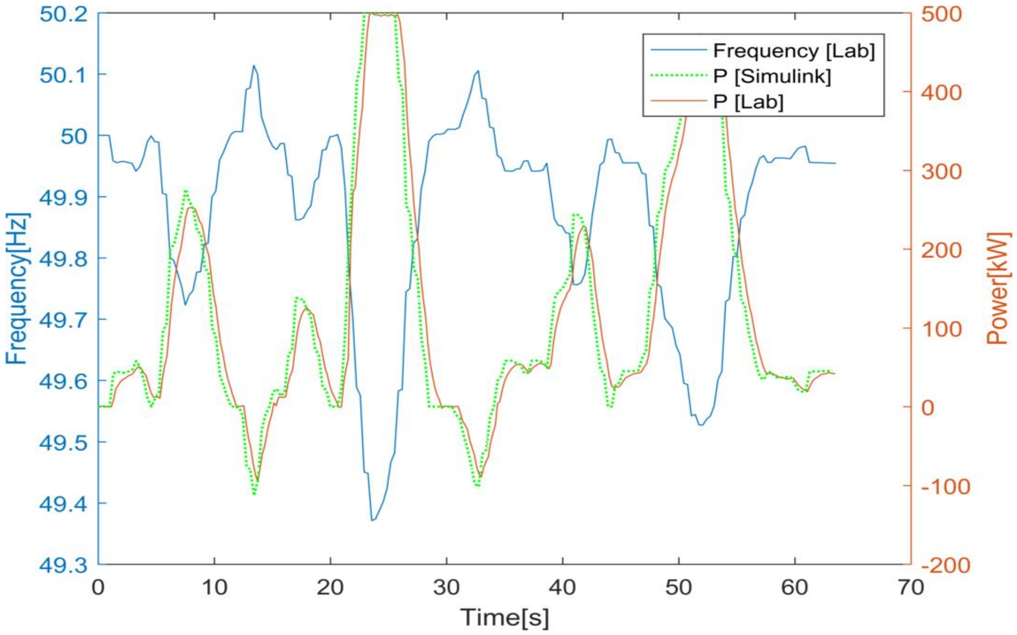


Figure 33 - EFR response for continuous frequency deviations

It is important to analyse the behaviour of all functions under different conditions, not just those events that are the main objective of said function. For instance, under the presence of frequency oscillations, while the function is not supposed to address and damp existing oscillations, it is also not expected to overreact and burden the system. We can see in Figure 34 that, with the default parameter values, the response of the system is fairly limited in magnitude: given that the oscillations correspond to small frequency deviations, the output from EFR is small too (remember that the nominal power of the unit was 500kW).

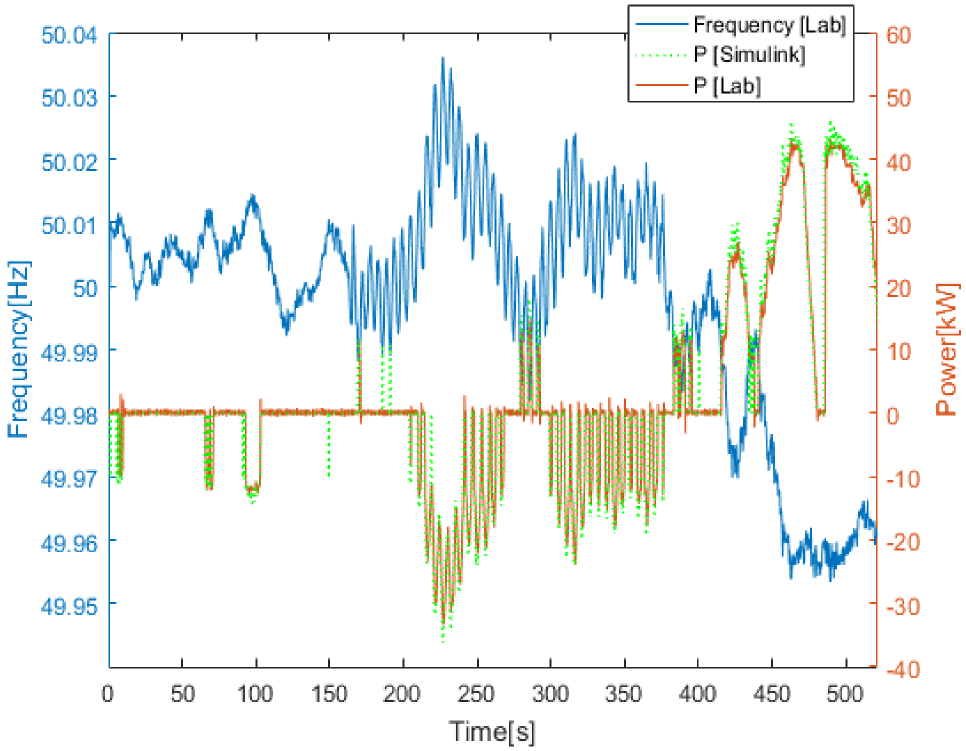


Figure 34: EFR response under frequency oscillations

In the next two tests the role of some design parameters and its influence in the response is evaluated. First, we modify the value of the frequency deadband: while traditionally in Continental Europe it is set to 10mHz, new ancillary services such as EFR might ask for different values of deadband, as dictated by National Grid in the UK. Notice in Figure 35 how a different value for deadband implies a shift in the time response, as it is activated later and therefore it stays active until *Thold* seconds have passed. Likewise, it ramps up at different time instants, since *Toff* starts as soon as the power reaches 0. For clarity purposes only the measured waveforms have been included in Figure 35 and not the expected response.

The system behaviour is also checked for different values of droop. Lower values of Δf_{max} imply a more aggressive primary response and, for large frequency deviations, delivering nominal power for a longer amount of time (see Figure 36).

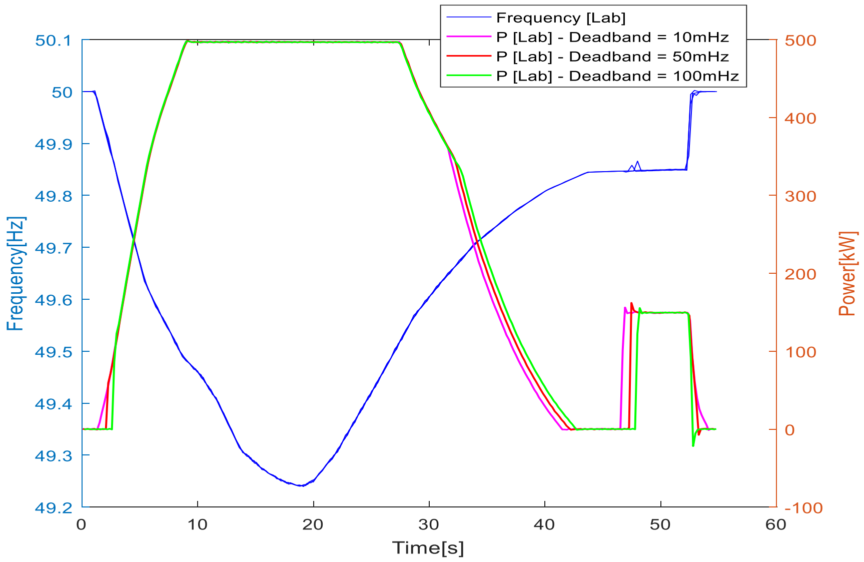


Figure 35: Effect of the deadband parameter in the EFR response

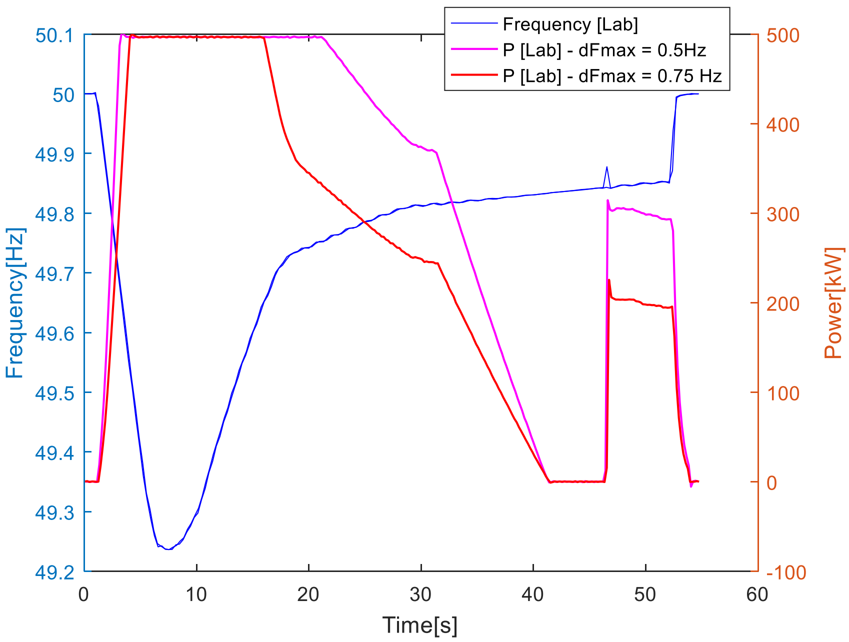


Figure 36: Effect of the droop parameter in the EFR response

6.4.2 Synthetic Inertia

In this set of tests, all functions but Synthetic Inertia are disabled. Frequency profiles associated with different values of RoCoF are used to evaluate the behaviour of the function. The default parameters for this function are:

- P = 500 kW (maximum power the function can deliver)
- H = 50 s (virtual inertia time constant)
- Ramp = 60 kW/s (maximum ramp rates)
- $(\Delta f/\Delta t)_{db}$ = 0.01 Hz/s (deadband for RoCoF values)
- Δf_{db} = 0.01 Hz (deadband for frequency)
- thres = 0.01 Hz (threshold value to define a hysteresis)
- tact = 0s (artificial delay or activation time)

- Inakt_En = 0,1 (corresponding to the triangular deadband)

As it will be later shown, this function is very sensitive to noise, hence a simulation model is not representative enough unless the noise (that will appear in a laboratory and in the field) can be fully characterized. Moreover, at the time of the lab tests, the internal computations for RoCoF implemented in the inverter were not fully known, as this was not uniquely specified in the function definition. This is indeed an open point (and a very relevant one) in assessing the full potential and corresponding drawbacks of this function. In general, this function does not clearly specify how the derivative of the frequency should be computed, especially taking into account the associated signal processing required to balance sensitivity of the function (to react fast enough) and robustness against noise. We describe here the sequential steps in the tuning of this signal processing stage.

We first test the function against two frequency steps of 0.4Hz in both directions. Even if this is not a realistic frequency profile, it is an adequate first step to evaluate the filtering properties and gain of the function. Given that this function is expected to be sensitive to noise, we run the experiment twice, and have obtained somewhat different responses, showing how the initial definition of the function and its filtering is fairly sensitive to noise.

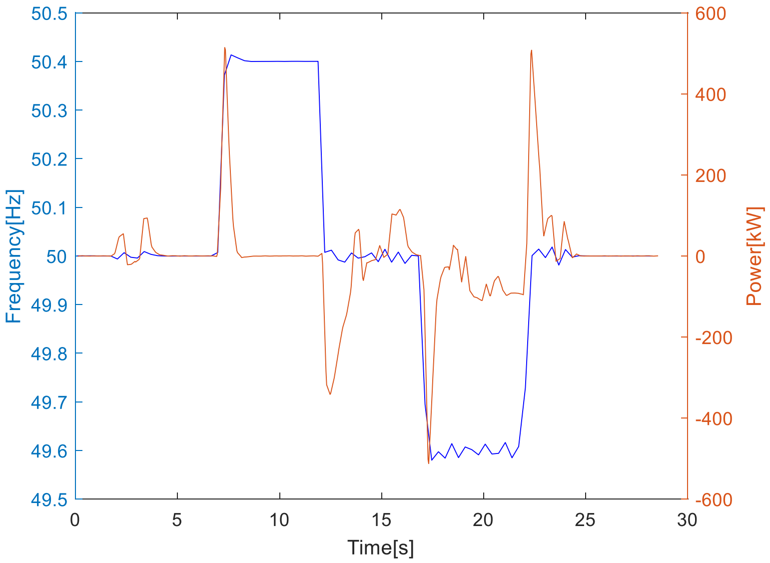


Figure 37: SI function under a frequency step (test I)

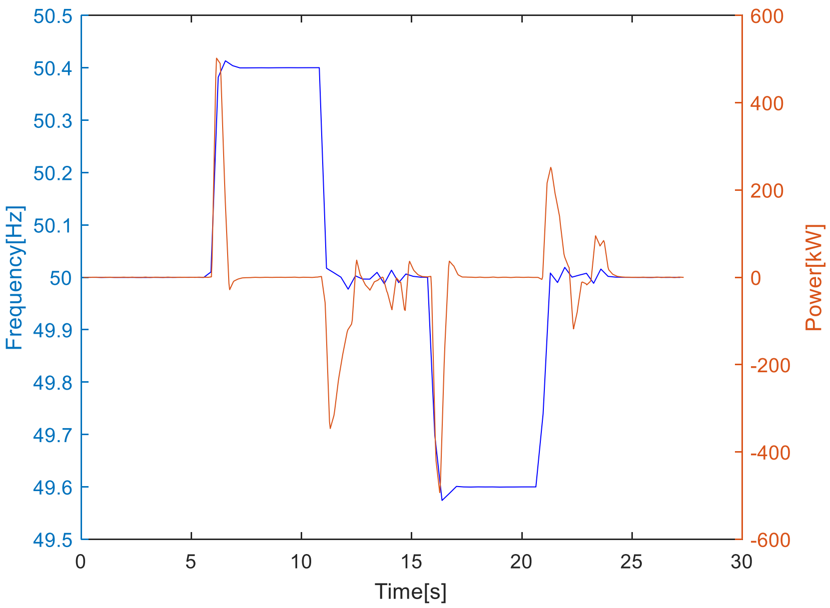


Figure 38: SI function under a frequency step (test II)

Given that this response is not desirable, the function and in particular the filter is modified to provide a clear response.

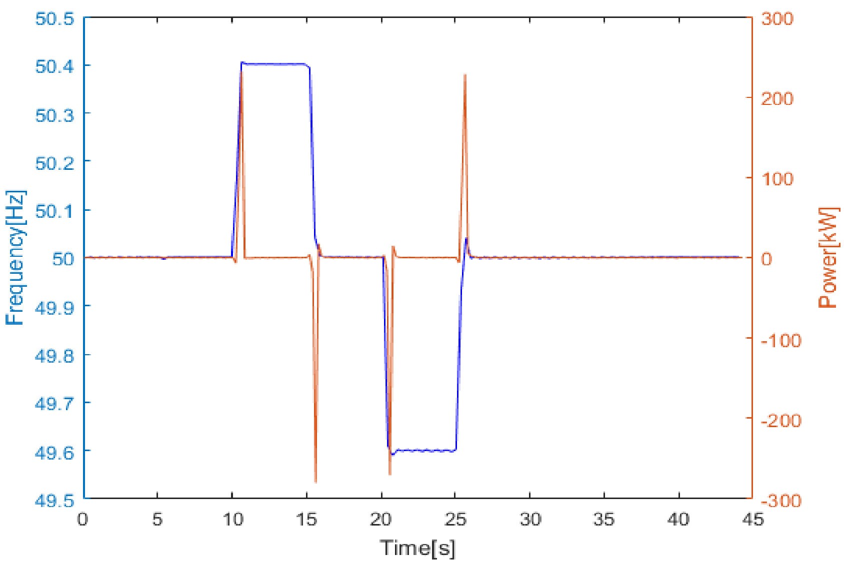


Figure 39: SI function under a frequency step (test III)

The response obtained in Figure 39 is much clear and satisfactory. We can therefore continue with more relevant and realistic frequency profiles.

We evaluate how the system responds under these filtering parameters for more realistic frequency profiles, see Figure 40. As for the EFR function, we excite the system with a frequency profile defined by ENTSO-E, characterized by a large nadir value and large RoCoF value. In this case, the triangular deadband has been activated, and therefore the response goes down to 0 right as the frequency reaches its nadir. While these set of parameters yield an optimal response for a step in frequency, the behaviour under more realistic frequency deviations is not optimal. The filtering parameters are tuned again to improve results, see Figure 41.

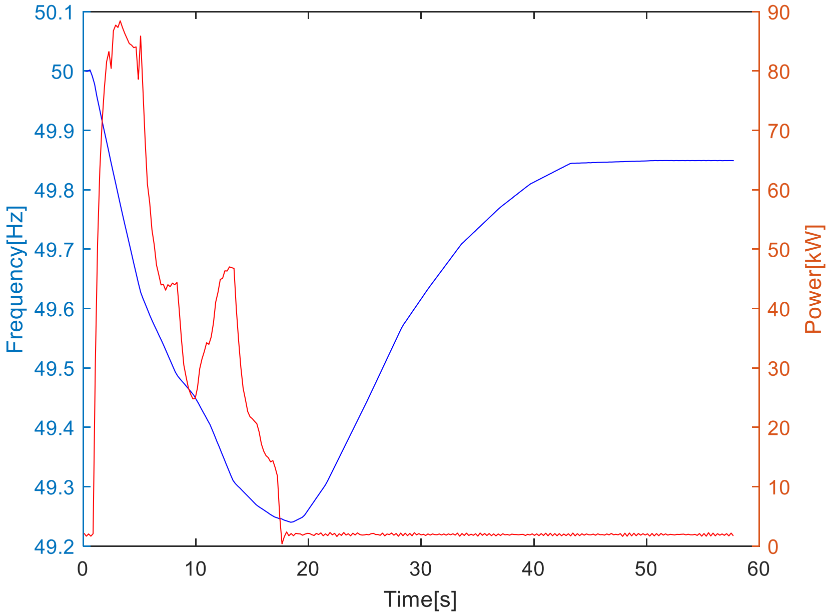


Figure 40: SI function under a slow frequency deviation (test I)

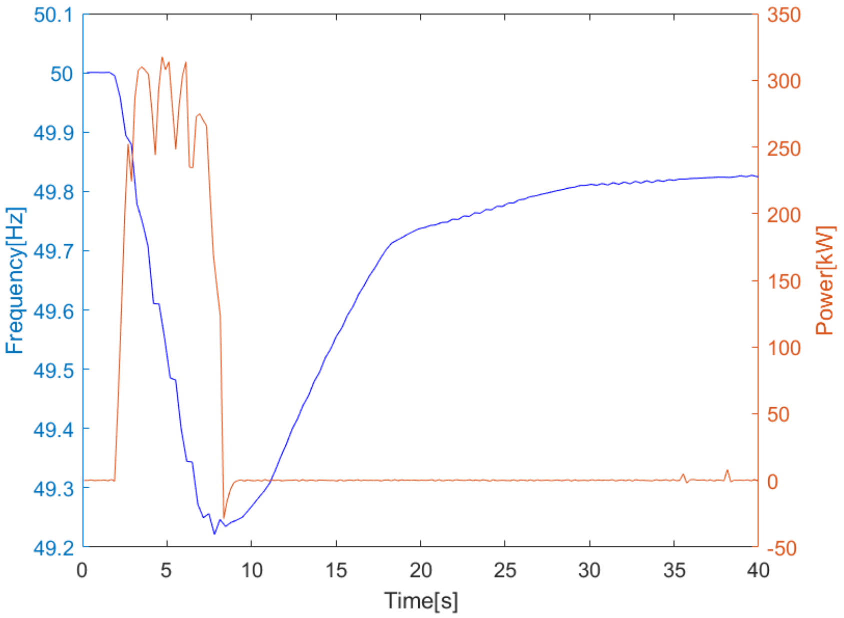


Figure 41: SI function under a slow frequency deviation (test II)

Nonetheless, the filtering is fairly sensitive to low frequency noise. We repeat the previous test adding noise (mainly low frequency noise), and observe continuous chattering in the output power (see Figure 42). Improving the filter in the function might fix this issue, at the expense of a delay in the response and a less aggressive response during minor events. Notice that having aggressive filtering implies introducing large delays that could cause oscillations and even instabilities, as pointed out by ENTSO-E. In any case, it is unclear though what type of noise properties and frequency components might be observed in the field, as it depends on many factors.

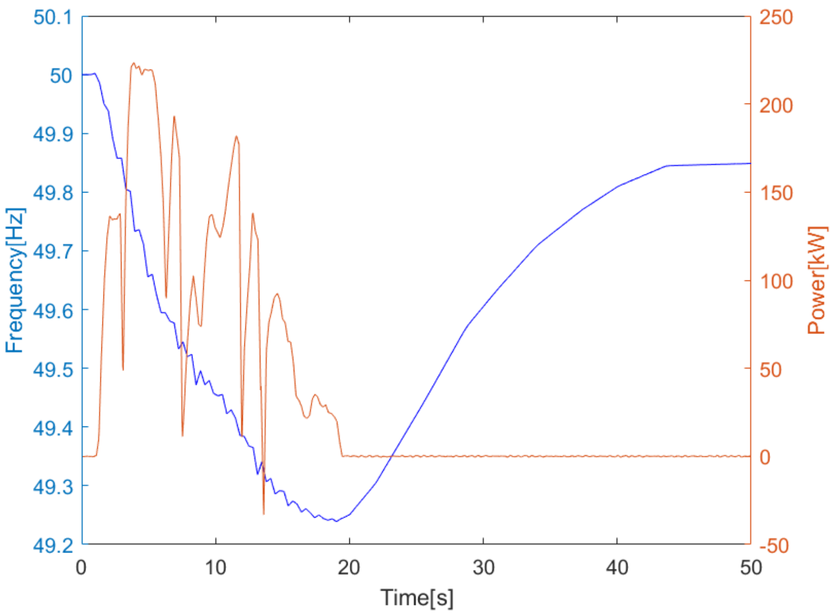


Figure 42: SI under a slow frequency deviation (test III), under low frequency noise

We repeat the experiment deactivating the triangular deadband. It can be observed in Figure 43 that the response is very affected by this low frequency noise, so the added benefits of this triangular deadband seem to be clear.

To further evaluate the filtering properties of the SI function, we apply a synthetic frequency profile consisting of a sequence of frequency ramps and segments of constant frequency (see Figure 44). The triangular deadband is active. It can be observed that the power output is affected by the filtering window, in the sense that, given the same RoCoF value, short ramps in frequency do not imply the same active power as in long ramps. Also, as the frequency returns to 50Hz (at around 80s), the unit also exhibits some chattering.

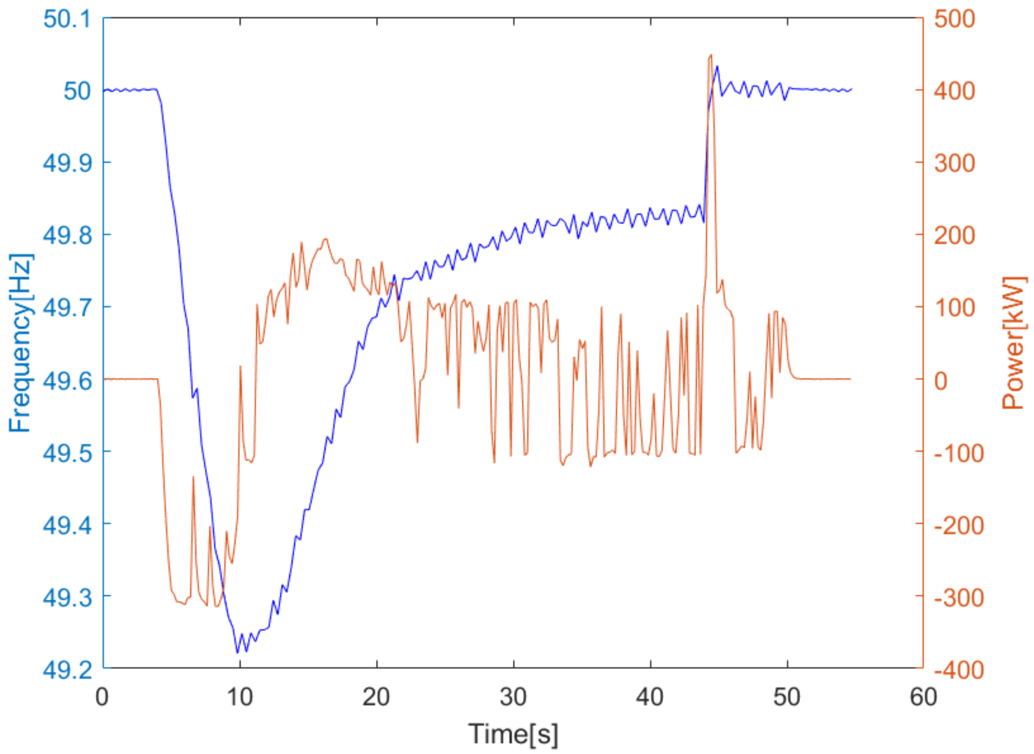


Figure 43: SI function under a large frequency deviation (with noise)

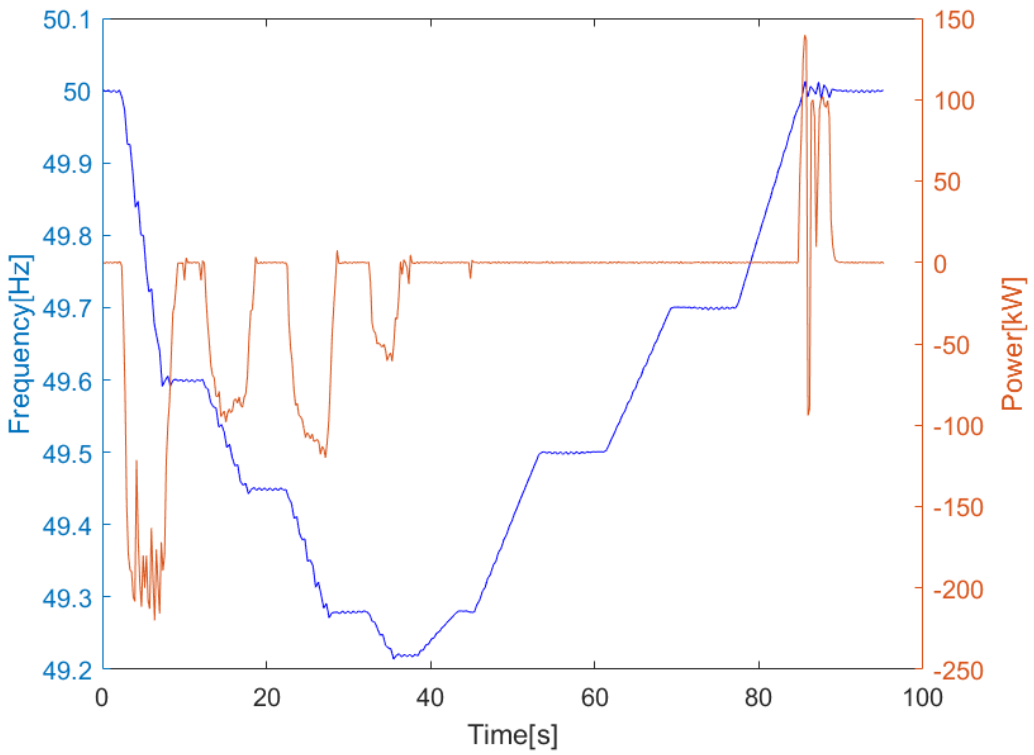


Figure 44: SI function for a synthetic frequency profile (test I)

These tests shed some light into the shortcomings of synthetic inertia. Synthetic Inertia is mainly implemented to address high-RoCoF events. It is therefore desirable that under other type of events the function does not act in an aggressive manner. Figure 45 shows the behaviour of this function under the presence of frequency oscillations. These oscillations are to be damped by power system stabilizers, and synthetic inertia should at least not worsen the grid frequency. In this case, we only see some spikes of low magnitude at some time instants, which is considered to be acceptable as it has no major impact on the frequency or on the energy requirements on the storage unit.

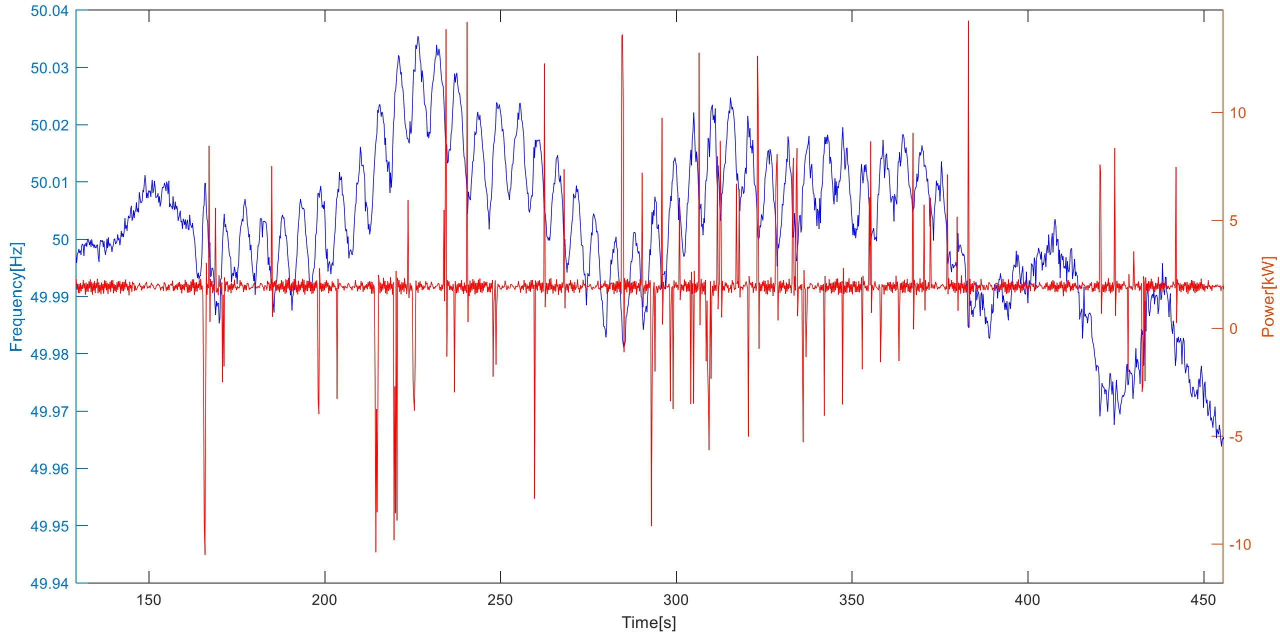


Figure 45: SI function under the presence of oscillations in the frequency

6.4.3 Deterministic Frequency Deviations

During this test only this function was active, as in the previous subsections. The DFD function can be seen as a time-activated EFR, and hence the expected response is very similar. The following parameters were used for these tests:

- P = 500 kW (maximum power the function can develop)
- Δf_{max} = 0.5 MW/Hz (droop or gain of the function)
- Δf_{db} = 0.01Hz (deadband in frequency)
- Thres = 100% (threshold to implement a hysteresis)
- Ramp = 6 MW/s (maximum ramp rates)

We test the DFD function against a historical deterministic frequency deviation, for different activation times. The function is supposed to be active as dictated by a time-varying parameter. Such an implementation allows us to explore the effects of different activation windows and its implications for frequency deviations and the state of charge (SoC) of the storage. The results are shown in Figure 46. For shorter windows, the DFD function starts ramping up to higher values, as the frequency deviation is already large. On the other hand, when the window is wider the function slowly ramps up its active power as the frequency exits the deadband. Hence, we can see this setting as being more conservative but at the price of being more energy intensive, as observed in the SoC evolution. Day-long profiles could be used to assess the impact on storage dimensioning to provide this service.

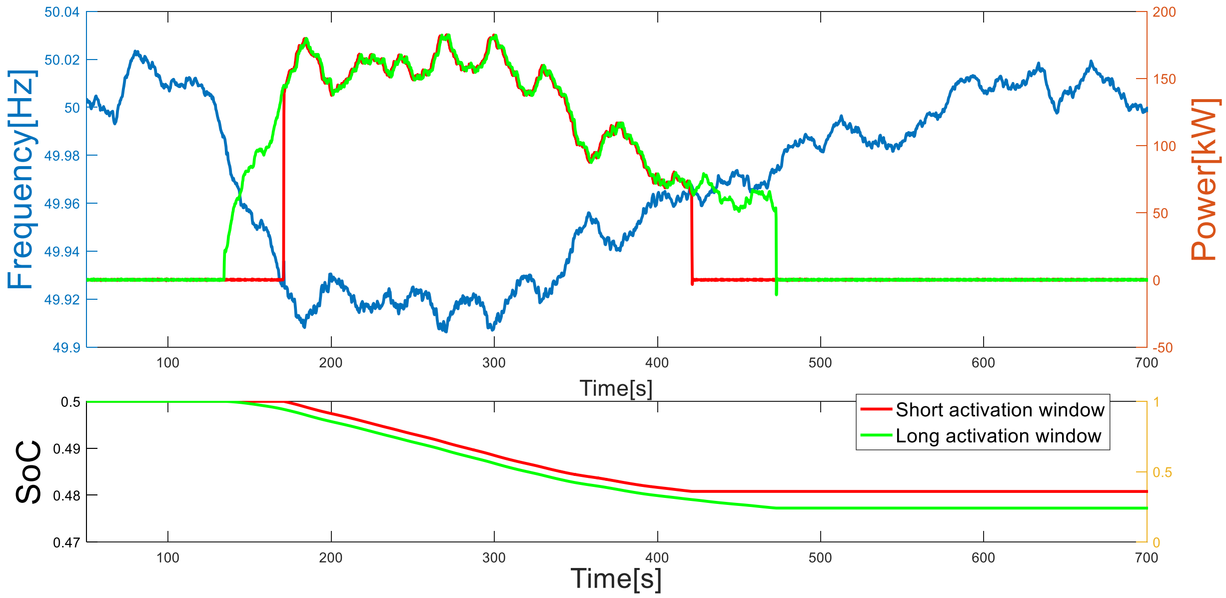


Figure 46: DFD response for two different activation windows

6.4.4 Multimodal operation

In the previous tests all functions were tested independently. In this section we explore and test the behaviour of the system when two functions are active. There exist many different possible combinations, we will consider here only a test where DFD and EFR are active, and another test where SI, DFD and EFR are active. Default values for all parameters were used.

We first evaluate the system response for a standard frequency profile proposed by ENTSO-E, corresponding to a large value of nadir. The test is executed 3 times, once with only the EFR function active, once with only SI, once with both functions active. It can be observed how the SI function provides a faster response in terms of active power, but dies down as the RoCoF value (df/dt) decreases, exactly when the EFR function takes over. Hence, for these type of frequency deviations, the EFR and SI functions are complementary and together provide an adequate response that mimics well the response of conventional power plants.

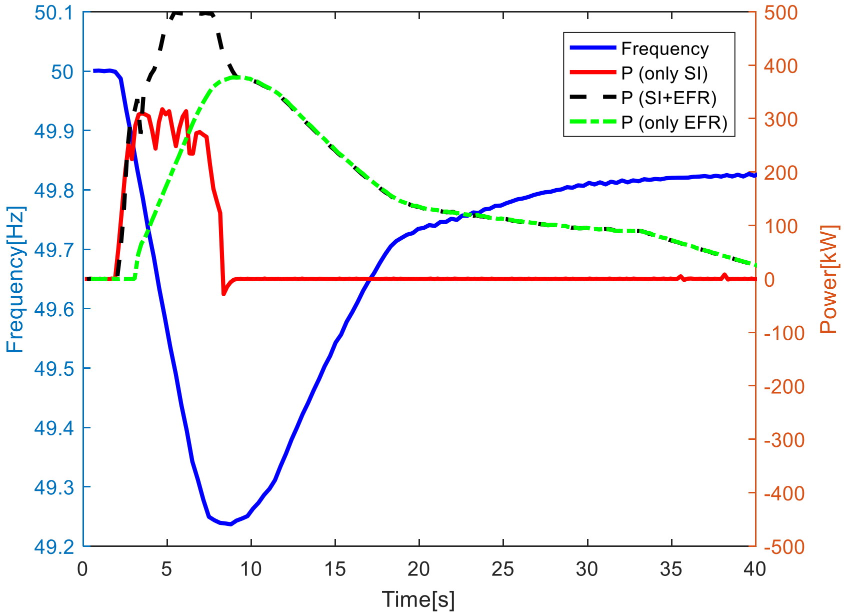


Figure 47: Multimodal operation (EFR+SI)

We further evaluate the system for a historical recording of a deterministic frequency deviation. The test is executed 4 times, once with the DFD function only active, once with only EFR, once with only SI, and finally once with the three functions active. First of all, the SI function requests no power as expected, since these type of fre4quency deviations are typically characterised by small RoCoF values and therefore SI would ideally not react. The EFR response is more aggressive than the DFD response (as it typically is parametrized with a higher droop value), but ramps down to 0 after a short period of time (*Thold*). On the other hand, the DFD response is active during the whole frequency deviation. Notice that the selected parameters might not be optimal, as it leads to a series of sudden increase in power output, whenever EFR is again active (as determined by *Toff*).

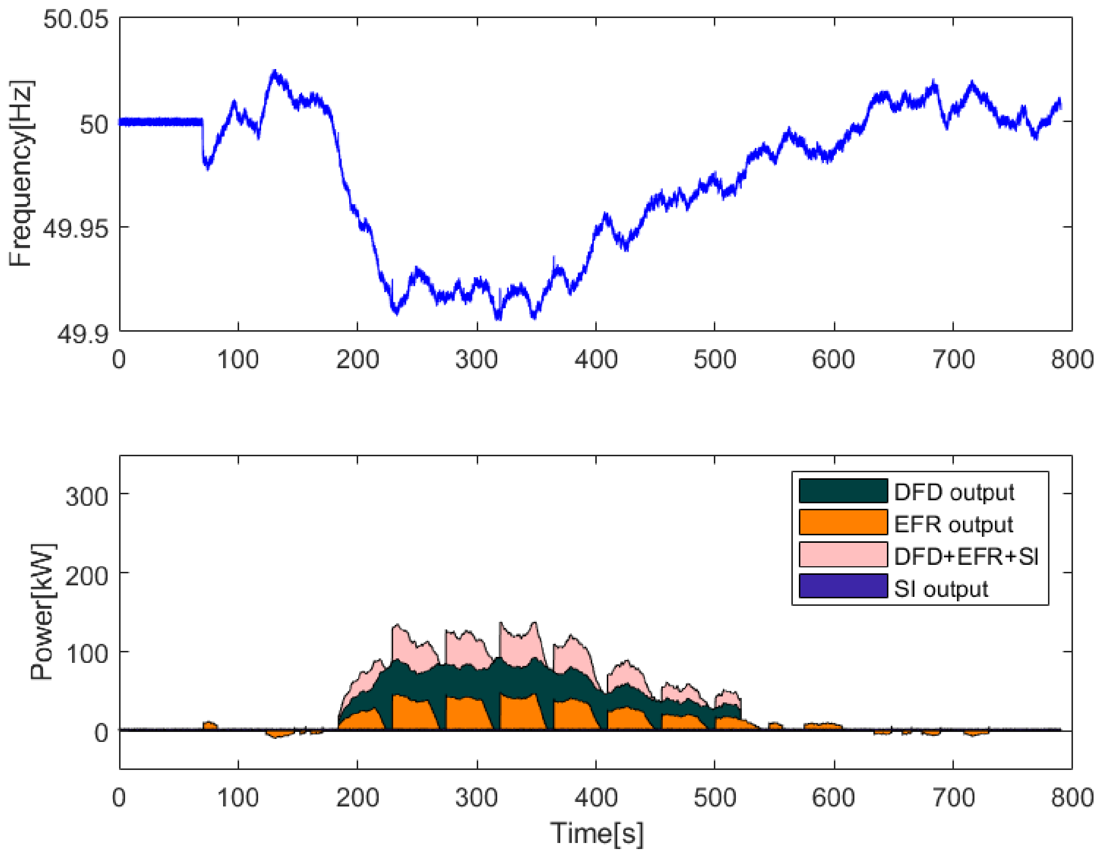


Figure 48 - Multimodal operation (EFR, DFD, SI)

6.5 Characterization of the frequency measurement of the storage system

Given that most of the system functionality is frequency dependent, the measurement procedure is of high relevance and can largely influence the behaviour of the storage system. The frequency estimation of the storage system and its accuracy has been analysed using a measurement system (Dewesoft Sirius). The frequency signal that is internally computed by a control board inside the inverter, and this is transmitted to a Dewesoft channel via CAN-Bus. The transmission rate corresponds to 30 values per second, and transient values that the internal PLL estimates can unfortunately not be monitored via CAN. Therefore, this study focuses on the steady state accuracy of the system. Using the c-HiL setup, a network model is used where a stiff grid generates a symmetric 3-phase sine wave with no harmonics where the frequency is changed in a step-wise manner, every 5 seconds. The frequency from the PLL read via CAN f_{CAN} is compared against the frequency from the measurement system f_{DEWE}.

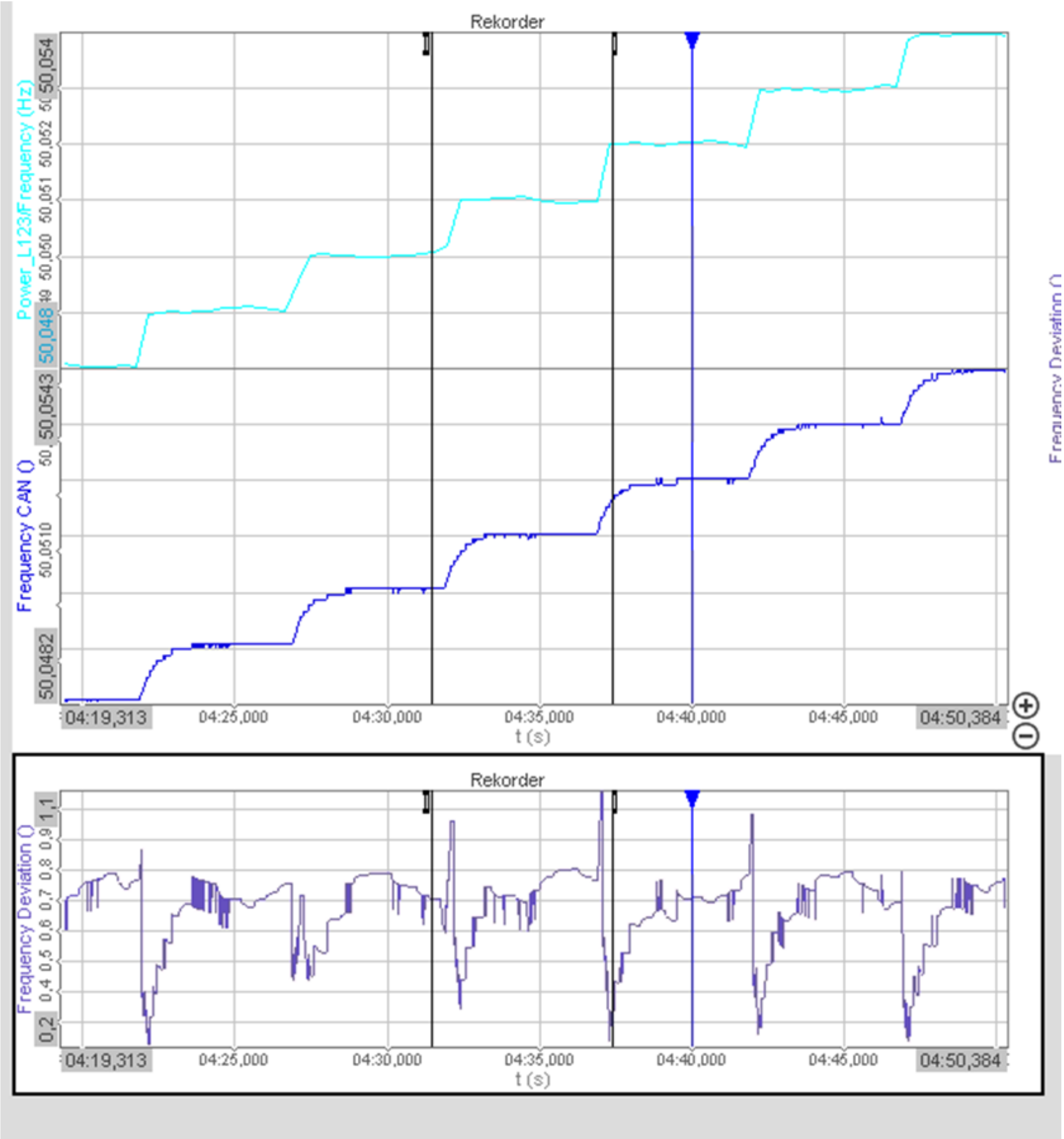


Figure 49: Frequency deviation during frequency changes

It can be observed that during the transients the deviations between the measurement and the expected value is larger, as each component uses different algorithms with different settling times. In this case, the internal board in the inverter has a slower transient.

In steady state these frequency deviations always remain below ±1,5mHz.
Notice that the system is equipped with additional frequency measurement devices such as PMUs, that allow us to identify during the field tests the accuracy and dynamics of the frequency estimation algorithm implemented in the inverter.

6.6 Grid-level impact of the functions at a large scale

In all previous tests a recorded frequency is used as an input in an open-loop fashion, that is, the behaviour of the unit does not affect the frequency. In other words, a single-machine-infinite-bus setup is considered. By means of an extra real-time simulator, the unit can be integrated with other units where the frequency depends as well on the functionality of the storage system. These tests have been carried out with the c-HiL setup, due to time constraints for the lab testing, and to leverage the flexibility of real-time simulators.

Many events and functions could be tested under this setup, given its computational power to replicate advanced power electronics and complex grids. We report here only the tests performed for the PSS function, to analyse the impact that delays might have in the performance of this function. A standard benchmark for this function is the 2-Area network, also known as Kundur example, containing 4 machines divided in two areas and two lines linking them. On top of this, the HIL setup is connected in one of the areas and scaled up to have an influence in the overall grid behaviour, as displayed in Figure 50.

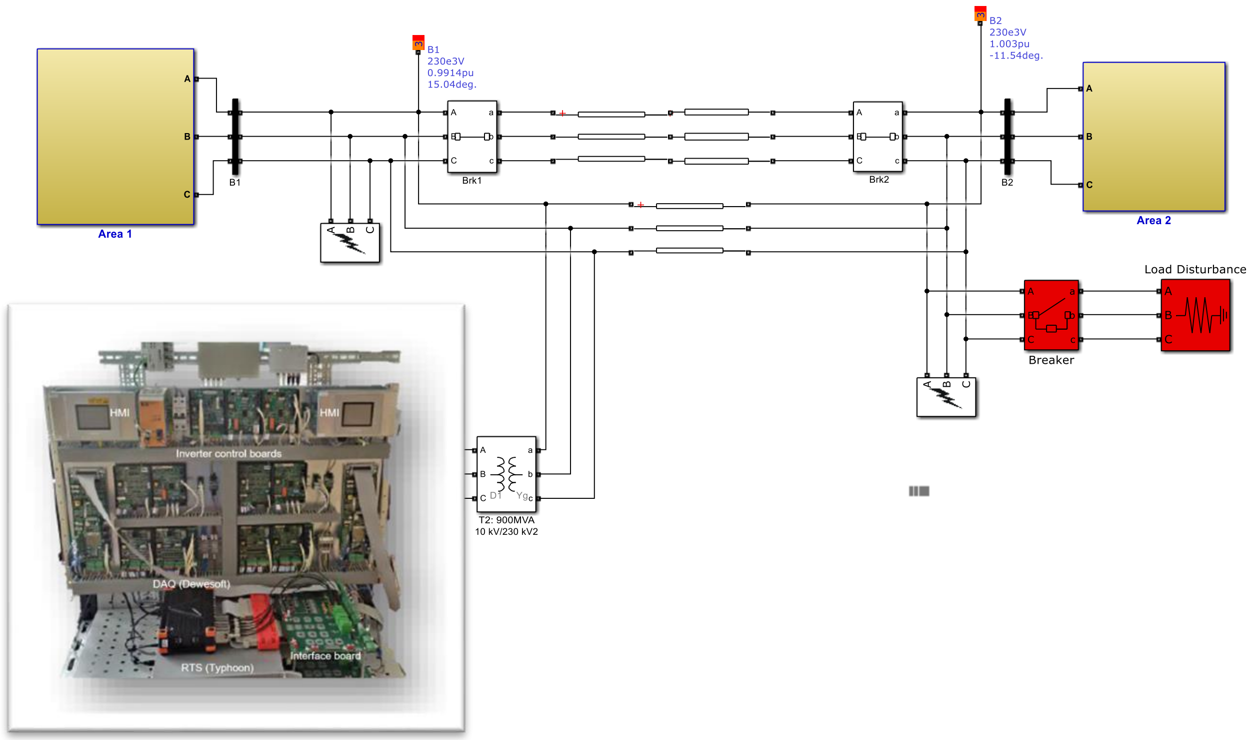


Figure 50: Two-Area network for PSS testing

Many tests were performed with this setup, to evaluate the impact of parameters, delays and measurements. For instance, if the inverter considers the measurements from the Area #1 (and unit 1), the PSS clearly improves the oscillations in the network, see Figure 51.

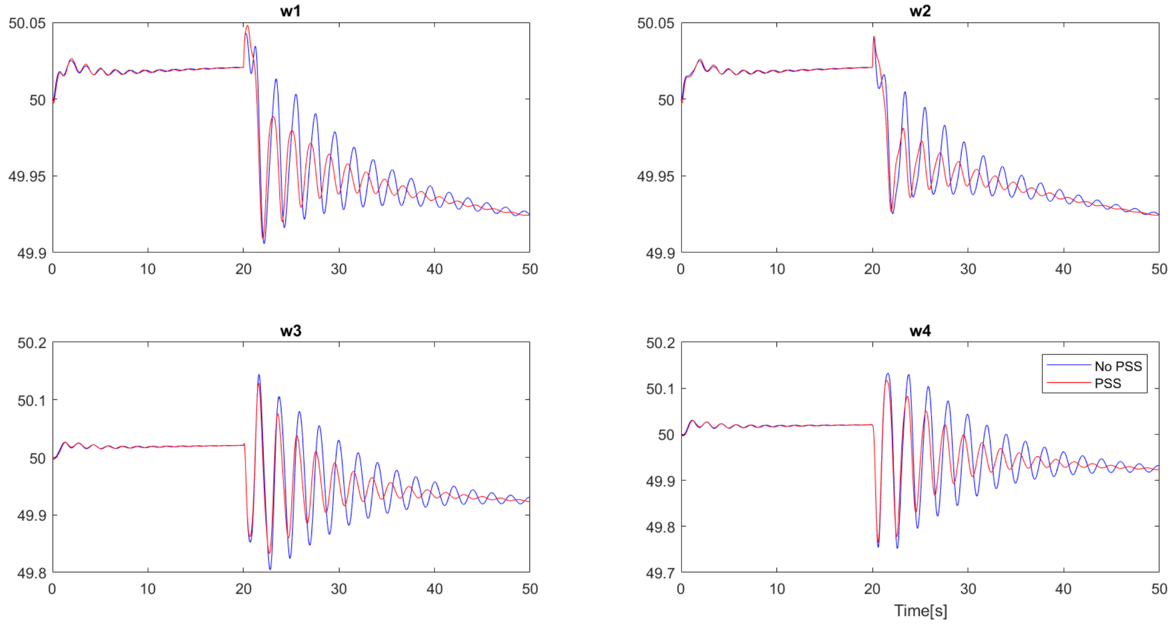


Figure 51: Speed in all machines with and without PSS.

We can also analyse the importance of using both inputs (frequency and power). Ideally, only the frequency measurement would be needed since measuring remotely the power at certain node is more convoluted.

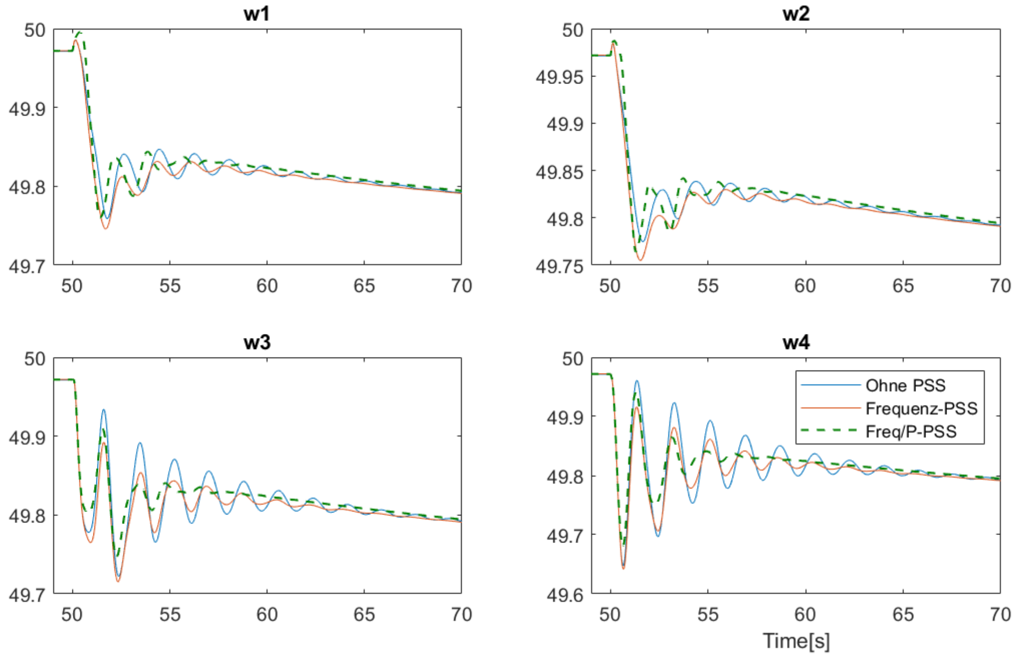


Figure 52 shows the decrease in performance when PSS only utilizes the frequency. Notice that in both cases (using frequency and power, or using only frequency) the same parameters have been used. There is the open question whether there exists an optimal design that minimizes the need for this extra measurement.

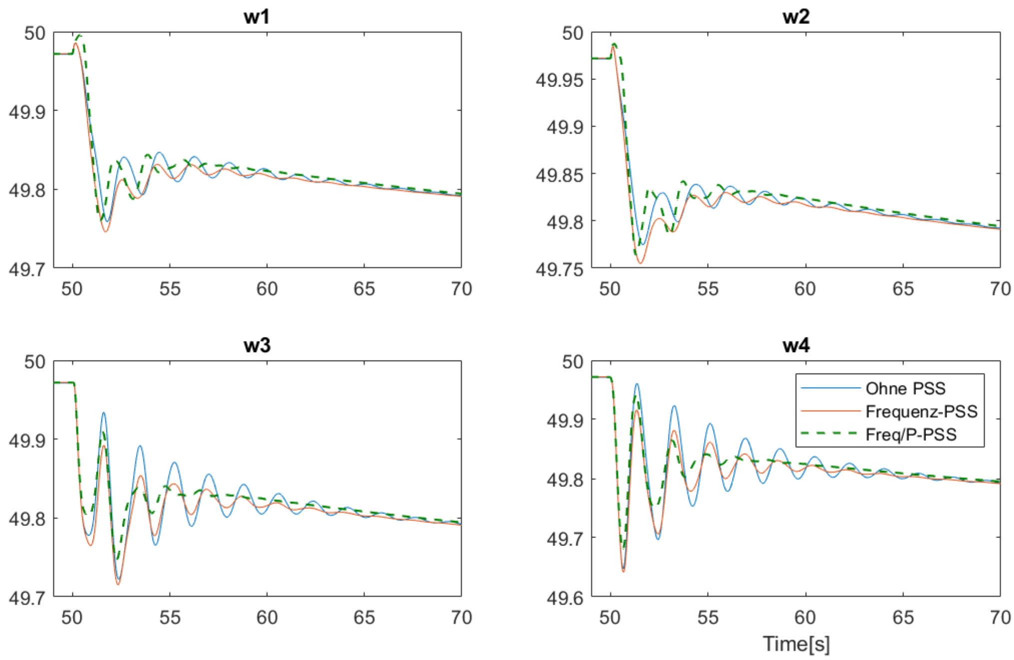


Figure 52: Frequency-only PSS vs Frequency & Power PSS

6.7 Characterization of the unit behaviour under recent frequency events

The hardware-in-the-loop setup combined with the automatization of all tasks and controls allows us to test the unit under different scenarios. In particular, and since the project experienced a delay in the field tests, the C-HiL setup is also used to partially replace these and evaluate the performance of the system under recent events. While dozens of frequency profiles were used, for brevity we show here just a couple of tests.

We explore the behaviour of the EFR and SI functions for an event occurred on January 8th, using different measurements at different locations. During this event two different isolated regions were created, one on the West experiencing an underfrequency, while the region on the East suffered from overfrequency (and relatively higher RoCoF values). Figure 53 reports the power provided under EFR for a holding time for the function of 30 seconds (according to the parameter *Thold*), which matches the specified behaviour. Nonetheless, some spikes can be seen every *Thold* seconds. While this makes sense, it is not an ideal behaviour, which points out that small values of *Thold* might not be adequate for long lasting frequency deviations such as grid splits. This was not observed before during other tests (in the laboratory or in the hardware-in-the-loop) as most frequency deviations are short enough. The holding time was accordingly adapted to 1800seconds (30 minutes), which removes these periodic spikes (see Figure 54). It can also be observed that the system is fast enough to react to the frequency deviation in a timely manner.

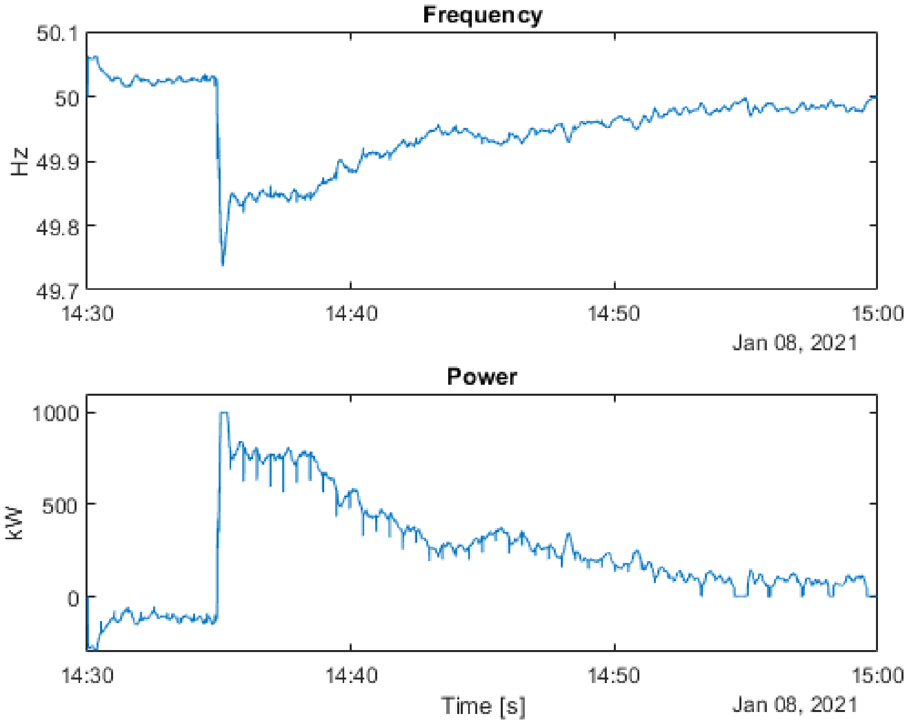


Figure 53 - Behaviour of EFR for a grid split event (Thold = 30s)

Figure 55 shows the response of the storage system when only SI is active, and for different frequency measurements located in the West region: Spain (ES), Denmark (DK), Croatia (HR), Italy (IT) and three additional locations in Austria (AT). This shows one of the issues with this function, namely that the behaviour depends largely on the location of the unit. Hence, it is difficult to aggregate its behaviour, making it hard to perform grid analyses and therefore to define clear criteria for a grid service. Figure 56 leads to a similar conclusion, this time for the East region. This region was smaller and therefore it is expected to be characterized by lower values of inertia, therefore RoCoF is a big larger and the power coming from SI is also relatively higher.

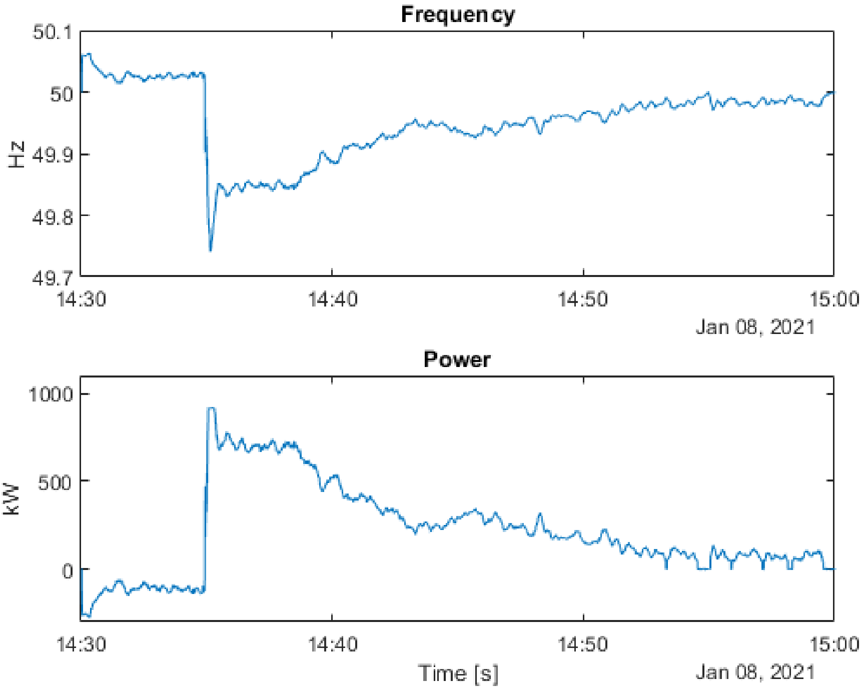


Figure 54 - Behaviour of EFR for a grid split event (Thold = 1800s)

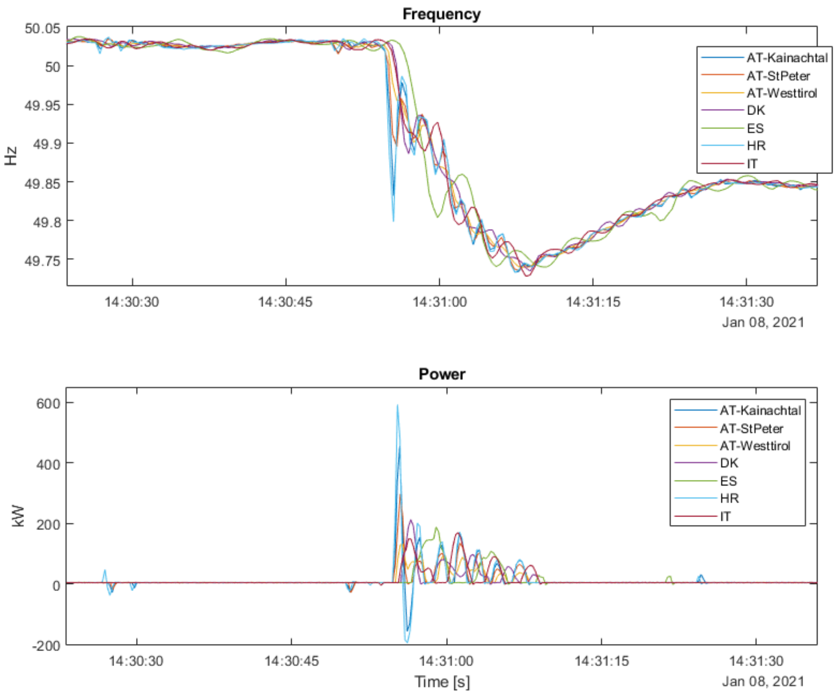


Figure 55 - Behaviour of SI for a grid split event using different frequency measurements (West region)

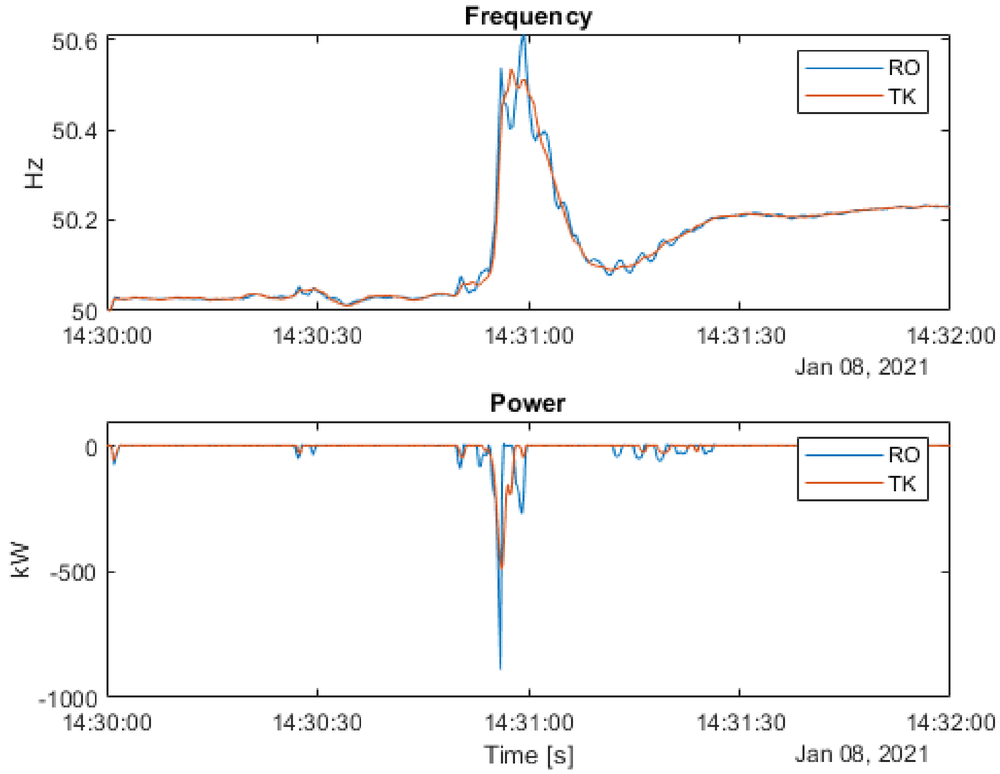


Figure 56 - Behaviour of SI for a grid split event using different frequency measurements (East region)

Finally, we report the results of combining SI and EFR functions for a typical frequency deviation from April 2017, with relatively high RoCoF values. It can be seen how SI provides an oscillatory response, mainly due to the filtering and irregular RoCoF values. EFR on the other hand does not suffer from this effect, and provides a consistent support. Notice that the reported values for EFR and SI are setpoints and not measured values, since only the total delivered power can be measured.

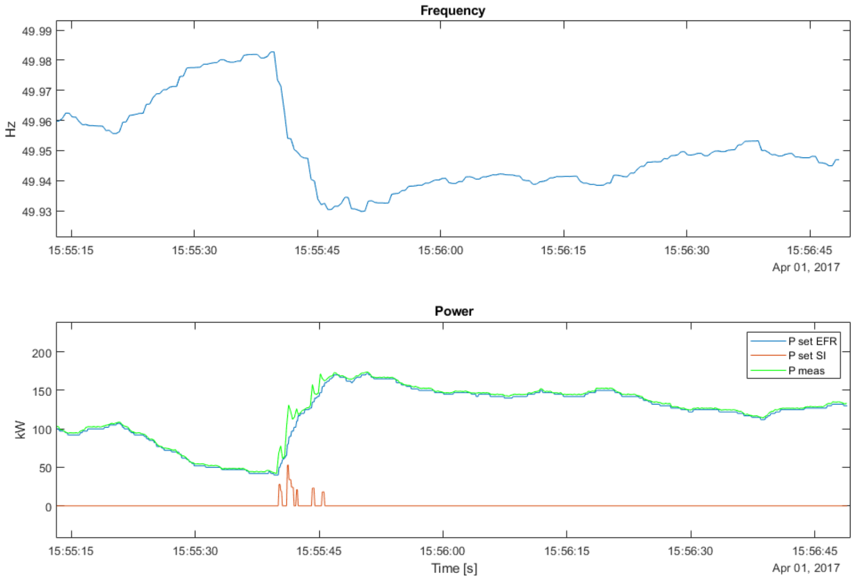


Figure 57 - Behaviour of EFR + SI during multimodal operation

6.8 Conclusions

The functionality of the system has been tested thoroughly in the laboratory and in the c-HiL setup with the help of a real-time system and a grid simulator. Different function parameters and frequency and voltage profiles were evaluated. While most functions were successfully tested, synthetic inertia poses some open questions regarding the robustness to noise in the field. Two functions (PSS and Post Fault Active Power Recovery) were only partially tested in the laboratory due to time constraints. The tests corresponding to these two functions were completed using the c-HiL setup, shedding some light into the behaviour of the storage unit for historical events and in a closed loop system where the proposed functionality is widely deployed.

7 Field tests

7.1 Introduction

Aim of the field tests is to validate the system behaviour of the newly developed fast balancing services on a real battery energy storage system. To do this a highly flexible 1 MW / 0.5 MWh battery storage system is used. Based on the real time measurement results, clear recommendations can be given for future product development.

The work package field tests covers everything from the

- Tendering process
- Detailed engineering with the supplier of the system
- Authorisation procedure
- Erection of civil and electrical infrastructure at the 380/220/110 substation
- Installation and commissioning
- Measurement and testing

7.2 Tendering Process

Aim of the ABS4TSO project is to investigate fast control functions to support grid behaviour. The newly developed functions should be tested on a real battery storage system. Since the newly developed functionalities are not available in standard power converter systems, a highly flexible, free programmable energy storage system is necessary for the prove of concept.

AIT prepared a detailed functional description of the energy storage system. The tender documents contained information about the planned fast balancing services and the measurement setup necessary to be able to verify each service.

The exact behaviour and the parameters of each function should be developed during the ABS4TSO project. Therefore this information was not fully available during tender phase. Due to this fact, the new storage system needs to be free programmable during the whole project phase. Out of this the supplier of the system could not use standard power converters which can only be parametrised, but not be reprogrammed, for this research oriented system.

During tendering phase 43 potential suppliers have been contacted to check their willingness to hand in a commercial offer. 25 out of 43 responded to this open call. To enhance attraction of the tender, the final invitation to tender included two systems. The research oriented ABS4TSO system (1 MW / 0.5 MWh) and a commercial battery storage system (10 MW / 10 MWh).

Finally three suppliers gave an offer for the ABS4TSO system. The most favourable offer was made by the final supplier SAET.

7.3 Detailed engineering with the supplier of the system

The detailed engineering of the storage system was done in close collaboration with the project partners AIT, APG, VERBUND and the supplier of the system SAET.

The final place of operation of the battery storage system is within a 380/220/110 kV substation of APG. The system is connected to a 10 kV auxiliary supply switch gear within the substation. Therefore, a high level of safety measures regarding the 10 kV medium voltage connection had to be taken into account for the design of the system.

The single line diagram showing the main components is depicted in Figure 58. The system consists of two containers. One container for the batteries and the power converters (Storage Container) and a second container for the low voltage distribution panel, the step up transformer and the medium voltage switchgear (Medium Voltage Container).

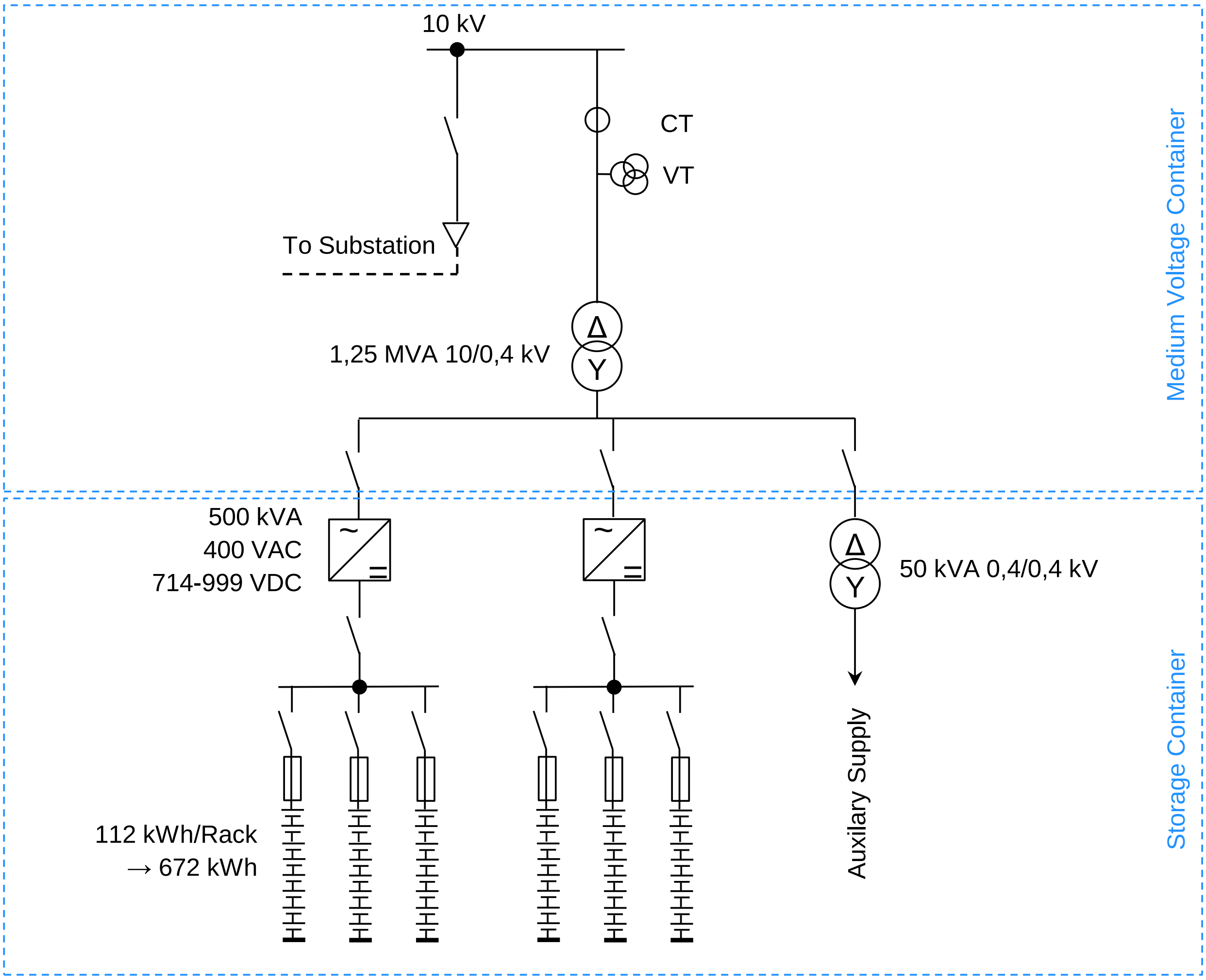


Figure 58: Single Line Diagram of the ABS4TSO system

The Layout of the energy storage system is shown in Figure 59.

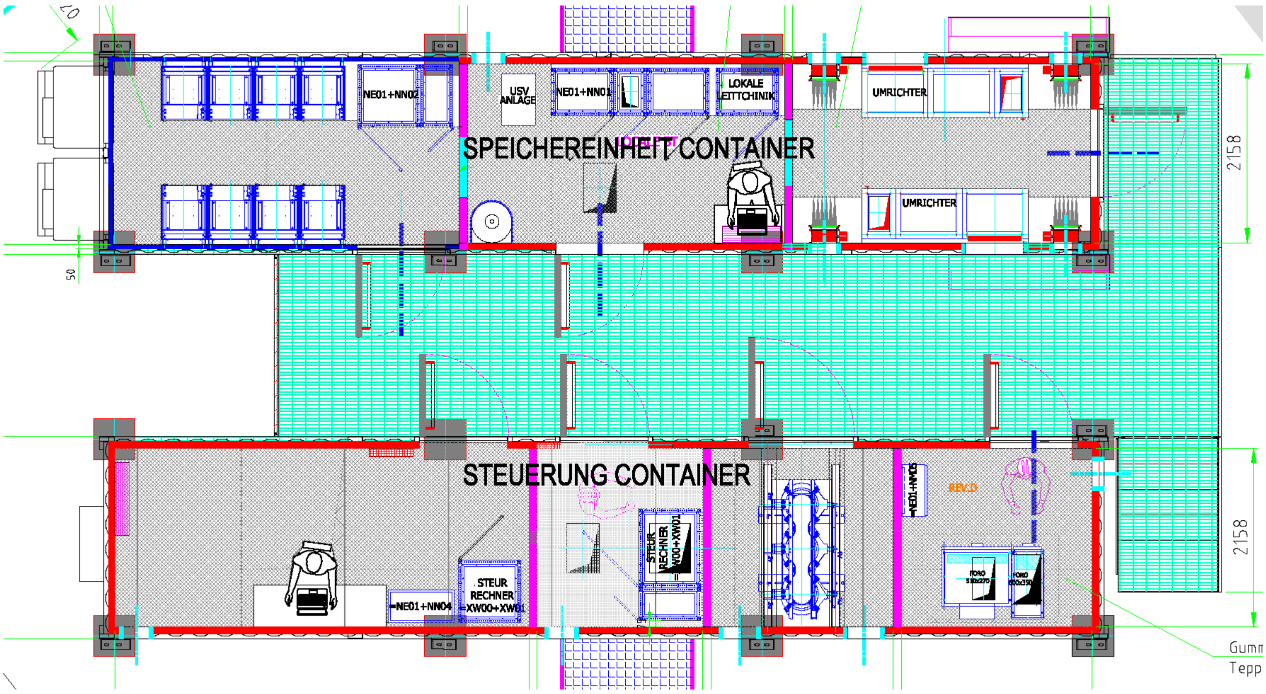


Figure 59: Layout of the energy storage system

The system is designed for a useable capacity of 500 kWh. Since the batteries must not be fully discharged, the installed capacity is higher (672 kWh) than the useable capacity. The battery-cells are of type LG Chem JP3 power cells, capable of fast charging and discharging in less than one hour. The cells are installed in modules. 17 modules are installed in one rack. Three racks connected in parallel result in one battery bank. Two battery banks are installed in the ABS4TSO system. Each battery bank is connected to a power converter. Each power converter can be individually controlled.

The ambient temperature of the batteries is quite crucial, therefore the temperature inside the battery room is kept at a constant level by an automatic HVAC system. The two power converters are of air cooled type. The battery room is equipped with an automatic fire suppression system.

The storage system is connected to the APG 10 kV grid by a 200 m medium voltage cable connections. Since the 10 kV grid is not a public MV grid, special operating conditions had to be taken into account for the connection of the system. In detail the network is operated without any star-point connection. Out of this special care had to be taken for the installed medium voltage switch gear, especially for the setup of the voltage transformers (VT).
Finally a 24 kV insulated switchgear had to be installed inside the MV container, even operated only at 10 kV. The VTs have to be capable to withstand voltages of 10 kV permanently, compared to 5.7 kV in a classical symmetrical 10 kV application.
In the tender a MV switchgear capable of withstanding a short circuit current of 31,5 kA was demanded. During detail design phase it turned out, that a switch gear 24 kV / 31,5 kA cannot be installed in a standard container due to height of the switchgear. Taking the 200 m cable

connection into account as a damping element a 25 kA switchgear turned out, to be sufficient for the final installation.

An independently operating electrical protection system is installed to protect the storage system itself and to disconnect the storage system from the 10 kV connection toward APG. Usually a high availability is necessary for systems providing balancing services. For this research task minimising negative effects on the auxiliary supply of the substation was demanded. In case of any internal failure, the storage system has to disconnect from 10 kV grid of APG. An automatic reconnection is not allowed.

The acquisition of real time data is performed by permanently installed equipment delivered by SAET and by additional highly precise measurement equipment installed by AIT.
The measurement equipment installed by SAET is necessary for the control and normal operation of the system, as it would be in a future commercial system. The measurement equipment installed by AIT is for research purpose only and is not used for system control.

7.4 Authorisation procedure

The ABS4TSO energy storage system is intended for temporary research purposes only. But due to the characteristics of the system e.g. medium voltage connection point, possibility of guided tours for interested people and so on, a full authorisation procedure according to Austrian law “Starkstrom Wegerechliches Genehmigungsverfahren” had to be completed.

During such a procedure the authority issues a list of requirements for the dedicated project.
The list of requirements for the ABS4TSO project includes the detailed design of the system.
The obligatory inspection of the system after commissioning by an independent third party.
The allowance to perform tests during commissioning phase of the system.
The final operation of the system is only allowed after handing in the acknowledgement of the independent third party to the Austrian authority.

Due to the fact that the short circuit withstand capability of the medium voltage switch gear was reduced from 31.5 kA as defined in the list of requirements, down to 25 kA for the realisation, a full acknowledgement by the independent third party could not be given. Therefore the system had to be shut down after commissioning, causing quite a delay in the overall project. After preparing all relevant documents showing that the 25 kA switchgear is suitable for the operation at the APG substation, finally acknowledgement by the independent third party could be given. After this the system could be put in full operation.

7.5 Erection of civil and electrical infrastructure at the 380/220/110 substation

The battery energy storage system got fully integrated into the APG substation. The main connection from APG to the storage system is done by a newly laid 200 m 10 kV medium voltage cable. Further on an additional 400 V low voltage connection was made to supply the auxiliary systems like HVAC, monitoring and control system and so on. For signal exchange a new fiber optic cable was laid. To prevent unintended earthing of the MV cable during operation, hardwired electrical interlocking between APG switchgear and ABS4TSO switchgear was installed.

Figure 60: Erection of the energy storage system at APG site

The two containers of the energy storage system are placed on 8 concrete blocks each (see Figure 60). Below the containers an additional copper earthing grid had to be installed. All metal structures and the external lightning protection system are connected to the earthing grid.

The final installation is shown in Figure 61.

Figure 61: Final installation of the system

7.6 Installation and commissioning

The commissioning of the storage system was performed in a two stage procedure.

In a first stage the storage container was delivered to the laboratory of AIT as described in chapter 5 Lab tests. In the lab of AIT the full functionality of the storage container, the batteries, the monitoring and control system and especially of the power converters was tested. Therefore only few commission works for this container had to be done on site.

The medium voltage container and all installed components were tested during factory acceptance test.
The interactions of the storage system and the 10 kV grid at APG substation could not be tested or simulated at factory level.

During powering up of the system it turned out, that the setup of the 10 kV voltage transformers was not compatible, with the measurement equipment of the power converters. Therefore new voltage transformers had to be ordered. The long lead time of the new VTs in combination with emerging COVID-19 crisis ended up in an additional time delay for the ABS4TSO project.

In the meantime the data connections, electrical interlocking and electrical protection systems toward APG substation were setup and tested.

After replacement of the VTs by new ones, commission works could be continued. Final tests covered testing of active and reactive power capabilities, charging and discharging of the batteries and initial testing of each implemented fast balancing service.

After finishing the authorisation procedure, the energy storages system was put in to full operation. Immediately afterwards real time measurements for the ABS4TSO project started.

7.7 Monitoring concept and measurements

Aim of the tests is to verify the effectiveness of the different fast balancing services and the interactions with a real energy storage system. Special attention was set to the state of charge (SoC) and therefore the available energy of the storage system during and after critical grid incidents. From these results, some main characteristics can be derived for systems, offering fast balancing services in future, e.g. the necessary power to energy ratio for each service.

For automatic testing, a script was developed to test different fast balancing services with varying parameters without any intervention of the operator. This is in line with the automatic lab and c-HiL tests that facilitates parametric studies. All data gathered from the battery energy storage system and the additionally installed measurement equipment is stored on a local PC. Since the storage system is embedded in an important substation, remote access to the monitoring and controls system is not allowed. Therefore, the stored data get automatically transferred to a cloud based data warehouse. So the members of the project team are able to access the measurement data without having any physical access to the monitoring and control system of the energy storage system. The analysis of the measurement data is performed offline by the project team. Moreover, different parameters and activation times for each function can be remotely uploaded via an FTP server.

Figure 62 describes how measurements are collected. From the inverter and the battery, analog signals from the DC and AC sides are measured using voltage and current transformers. On top of this, data from controllers and external measuring devices such as PQ analysers and PMUs are collected through Dewesoft and later uploaded to the data warehouse. The list of signals to be measured include the setpoints in active and reactive power, state of the battery and the estimated frequency from different devices. Being able to measure the same signal via different devices allows us to compare accuracies and define in a better way proper specifications for requirements on precision. It also contributes towards finding appropriate frequency estimation algorithms for fast-frequency services.

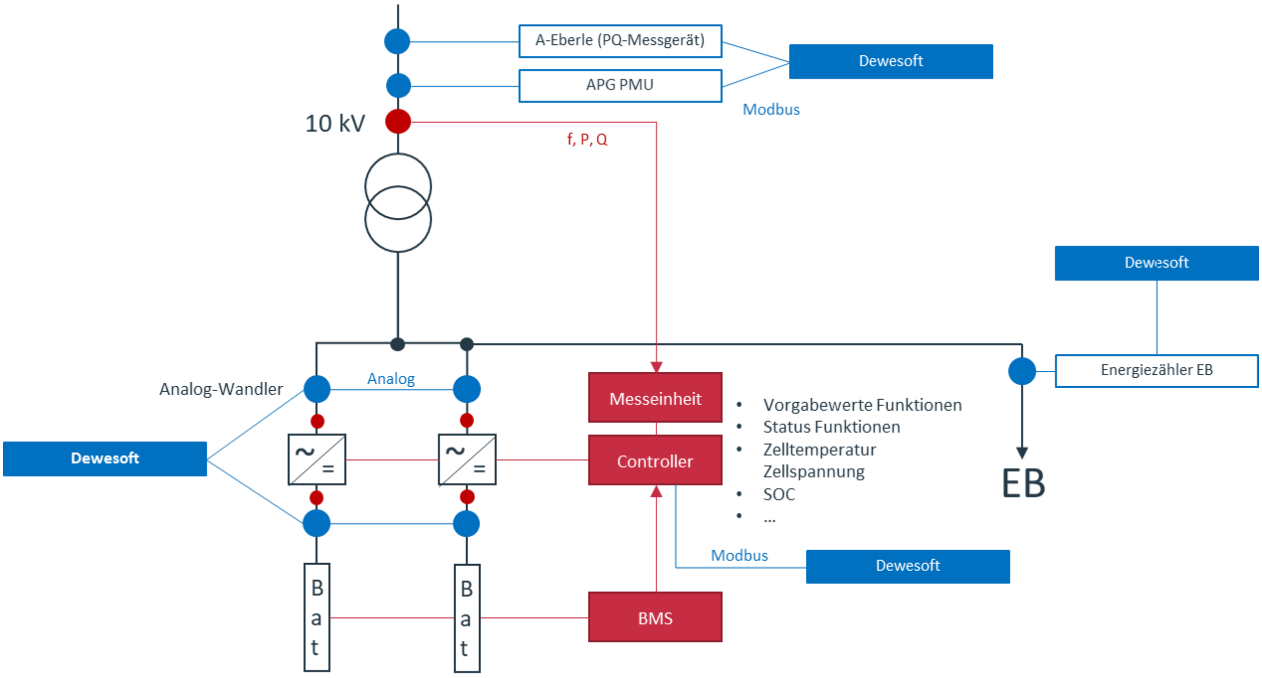


Figure 62: Measurement concept for the battery storage

All the measured data is stored in a database, first locally in the container and then periodically uploaded to a server that can be accessed remotely via a Web client. The graphical user interface allows the user to do pre-processing tasks or queries on the recorded data, and monitor the internal state of the battery cells, among other functionality (see Figure 63 for a snapshot of the battery monitoring tab).

Figure 63: Screenshot of the graphical user interface to monitor the storage unit

7.8 Description of the field tests and adaptation of the functions

In this subsection we first re-evaluate the parametrization of the frequency-control-services presented in Chapter 5.4 for their examination as part of the field tests. This is necessary to guarantee a sufficient number of events with active frequency-control-services despite the limited duration of the field tests as well as to control the proper functioning of every parameter. Accordingly, several different parameter variations are investigated during the field tests, which will be shown in the following sections. It is to be noted that FAPI is not investigated during the field tests and therefore an adapted parametrization is not necessary.

7.8.1 Frequency Containment Reserve Plus (FCR+) and Enhanced Frequency Response (EFR)

Since FCR+ and EFR are somewhat similar and the field tests require comparable set points for their frequency deadband and full activation frequency values, the field tests do not differentiate between these two functions. However, a wider range of parameters is considered to cover both functions and the differences in their design. The considered parameter variations for FCR+ and EFR are listed in Table 8.

Table 8: Parametrization of FCR+ for the field tests

Parameter	Unit	Test 1	Test 2	Test 5	Test 6	Test 8 & 11	Test 9
P	MW	1	1	1	1	0,5	0,5
Δf_{max}	Hz	0.2	0,2	0,2	0,2	0,2	0,2
Δf_{db}	Hz	0	0	0,05	0,05	0	0,05
T_{act}	s	0	0	0	0	0	0
T_{full}	s	0	5	0	0	0	0
T_{hold}	s	30*60	30*60	30*60	30*60	30*60	30*60
T_{back}	s	0	0	0	45	45	0
T_{off}	s	0	0	0	180	180	0
Remark		FCR+	FCR+	EFR	EFR	FCR+	EFR

Because of the combined investigation of FCR+ and EFR, Table 8 only includes "P" for the power instead of the respective parameter names from Figure 7 and

Figure 8. The values of "0" for T_{act}, T_{full} and T_{back} mean that no predefined delay is used and the actual frequency measurement time and full activation time of the BESS apply. Additionally, Table 8 considers a time T_{off}, which describes the time between subsequent activations.

7.8.2 Synthetic Inertia (SI)

In case of SI also different values are considered for the field tests. The corresponding values are listed in Table 9.

Table 9: Parametrization of SI for the field tests

Parameter	Unit	Test 3	Test 4	Test 8 & 9	Test 11
P_{SImax}	MW	1	1	0,5	0,5
$(\Delta f/\Delta t)_{db}$	Hz/s	0	0.005	0	0.01
$(\Delta f/\Delta t)_{max}$	Hz/s	1	1	1	1
Δf_{db}	Hz	0	0	0	0
T_{act}	s	0	0	0	0

Upon commissioning, the first field tests were carried out using active power and reactive power control. Once this was verified to work properly, simple frequency events were artificially created by modifying the internal frequency reference (via a function called frequency shift), that is in normal conditions set to 50 Hz, to roughly evaluate the steady state behaviour of EFR. After this set of preliminary tests, a calendar to test all functions under real frequency deviations was set (see Table 10). After a general test phase where different parameters and functions were evaluated to assess the proper implementation of the test procedures, the first two weeks were dedicated to FCR+ (selected in the SCADA as EFR, with different parameters each week), the next two to SI, the next two to EFR, and so on. Given the time constraints, one week was dedicated per test, even if during said week no significant frequency deviation occurs in the grid.

Table 10: Overview of the calendar for field tests

Field Test Calendar							APC	RPC	DFD	EFR	PSS	SI	FS	SR
Fri	Sat	Sun	Mon	Tue	Wed	Thu								
October														
1	2	3	4	5	6	7	GENERAL TEST PHASE							
8	9	10	11	12	13	14								
15	16	17	18	19	20	21				TEST-001				
22	23	24	25	26	27	28				TEST-002				
November														
29	30	31	1	2	3	4						TEST-003		
5	6	7	8	9	10	11						TEST-004		
12	13	14	15	16	17	18				TEST-005				
19	20	21	22	23	24	25				TEST-006				
26	27	28	29	30	1	2				TEST-008		TEST-008		
December														
3	4	5	6	7	8	9				TEST-009		TEST-009		
10	11	12	13	14	15	16			TEST-010					
17	18	19	20	21	22	23				TEST-011		TEST-011		
24	25	26	27	28	29	30				TEST-011		TEST-011		

Field Test Calendar							APC	RPC	DFD	EFR	PSS	SI	FS	SR
Fri	Sat	Sun	Mon	Tue	Wed	Thu								
October														
1	2	3	4	5	6	7	GENERAL TEST PHASE							
8	9	10	11	12	13	14								
15	16	17	18	19	20	21				TEST-001				
22	23	24	25	26	27	28				TEST-002				
November														
29	30	31	1	2	3	4						TEST-003		
5	6	7	8	9	10	11						TEST-004		
12	13	14	15	16	17	18				TEST-005				
19	20	21	22	23	24	25				TEST-006				
26	27	28	29	30	1	2				TEST-007		TEST-007		
December														
3	4	5	6	7	8	9				TEST-009		TEST-009		
10	11	12	13	14	15	16			TEST-010					
17	18	19	20	21	22	23			TEST-011					
24	25	26	27	28	29	30			TEST-011					

For brevity reasons we report here only the most relevant outcomes of the field tests.

- **FCR+**

  The first two weeks were dedicated to FCR+ with different parameters. Figure 64 shows the response of the storage unit, which matches the expected behaviour. The fast response of the system implies that some chattering will be observed whenever the frequency is around the dead band. Such an effect can only be avoided if the reaction of the system is artificially slowed down, by means of the parameters T_{act} (activation time) or the ramp rates (implicitly defined via T_{full}). It could also be achieved through a hysteresis band, but setting up uniform values for the hysteresis can be tricky as the frequency can oscillate around different values. Figure 65 compares the specified characteristic curve (power vs frequency) for the function and the measured values, for the same time series. The points outside the curve are caused by an inherent delay between power and frequency, due to the control loop.

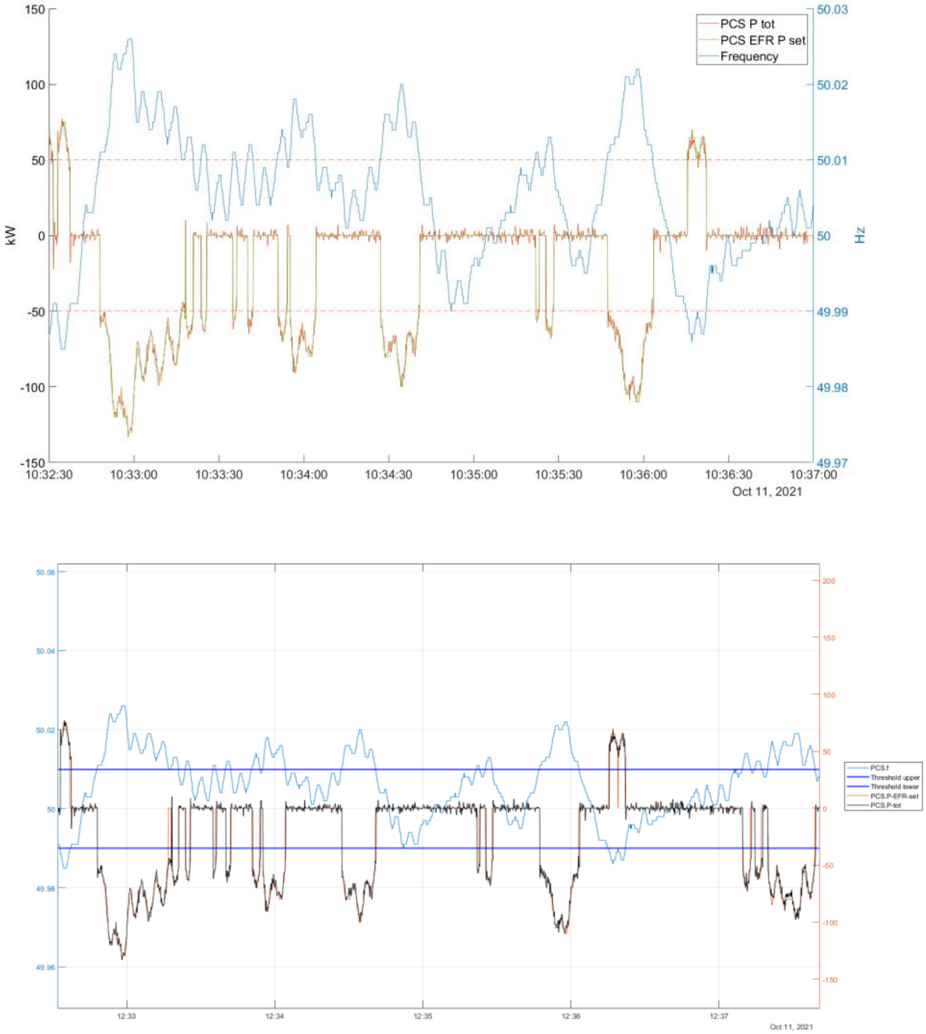


Figure 64: Behaviour of FCR+ with a deadband of 10mHz

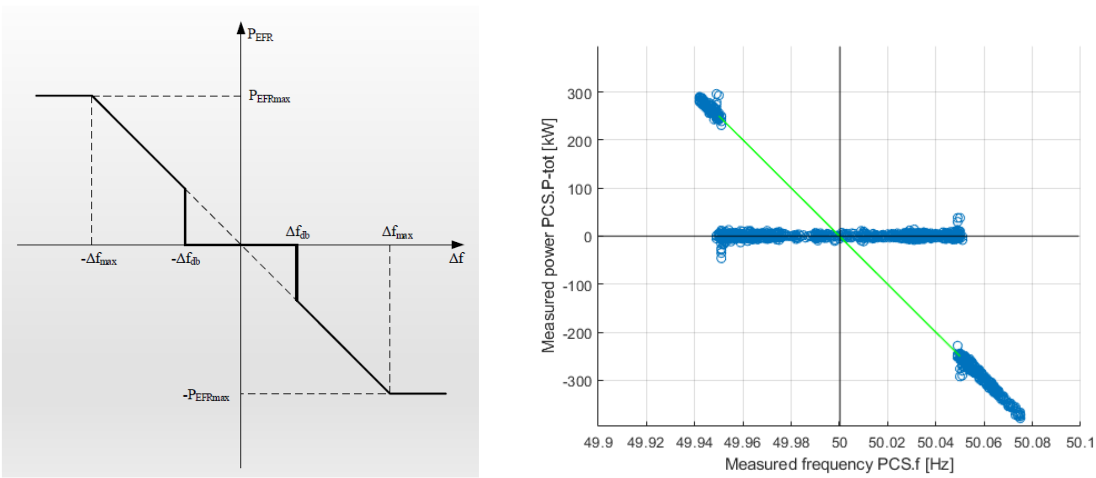
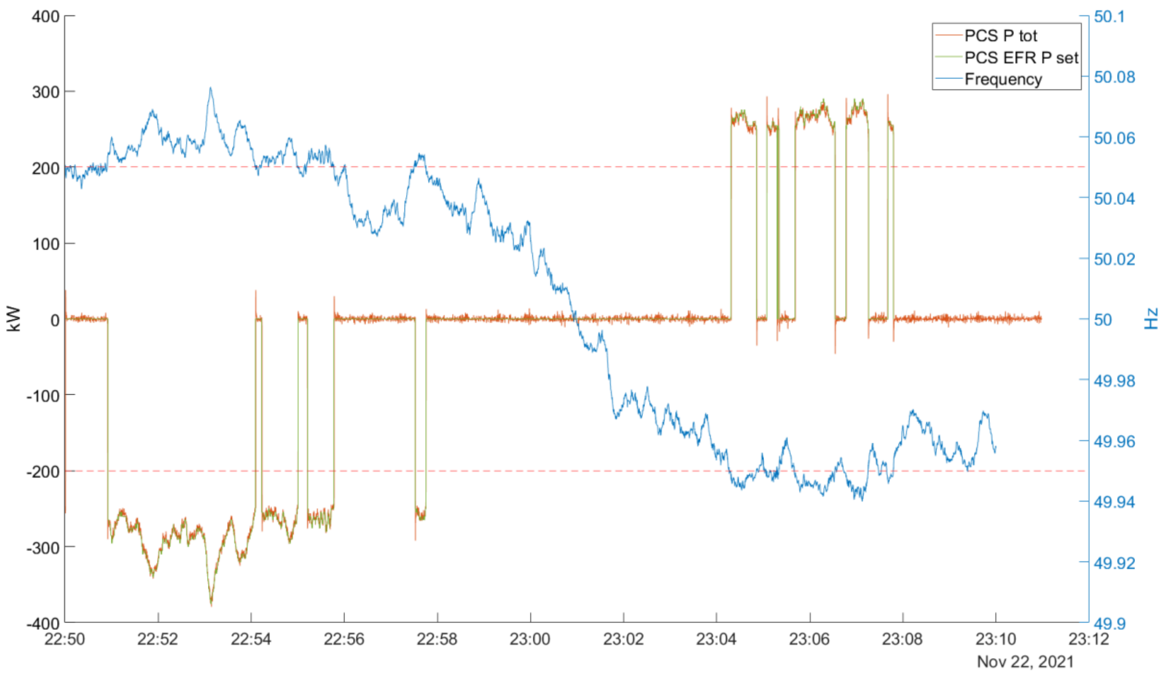


Figure 65: Specified static characteristic curve of FCR+ (left) and measured characteristic curve (right)

- **Enhanced Frequency Response**

  No large frequency deviation was observed during the weeks where EFR was tested, but nonetheless the frequency went outside the deadband, causing the storage unit to react providing or storing power. As in the case of EFR, some non-smooth behaviour is observed, caused by the prompt response characteristic of inverter-based generation (see Figure 66). Likewise, the characteristic curve was computed and coincides with the specification for this function. In this case, only the points around the deadband



  could be verified since no large deviation was observed.

Figure 66 - Behaviour of EFR, deadband set to 50 mHz

- **Synthetic Inertia**

  The parameters of the SI function were set in order to make the function extremely sensitive and able to react at very small frequency events, since no large RoCoF event is expected in the European grid. Although the behaviour of the system is not fully linear, it does give us a feeling on how the system would behave for large RoCoF events under a more conservative set of parameters. The deadbands were set to very low values and the gain of the function was maximized, within the limits of the storage unit.

  Figure 67 shows the power defined by the function (PCS.PSI-Set) for some small oscillations occurring in the grid, corresponding to fairly low values of RoCoF. As was already observed in the c-HiL tests, these low frequency oscillations can cause an oscillatory response in the system. Notice that for these tests the function does not deliver power if the frequency and RoCoF have different signs. Nonetheless, the behaviour might not be adequate since, ideally, the function would not react to these oscillations. Of course it is possible to set parameters that would make the function less sensitive, but this would come at the expense of diminishing the response the system for significant RoCoF events.

Figure 68 shows the time evolution of SoC for several days under SI. Since no large RoCoF event occurred, the amount of power to be delivered by SI is negligible, and therefore the SoC of both battery modules decrease linearly over time, slowly but steady. The battery is recharged from a defined 35% to the targeted 50% SoC every 12 hours approximately.

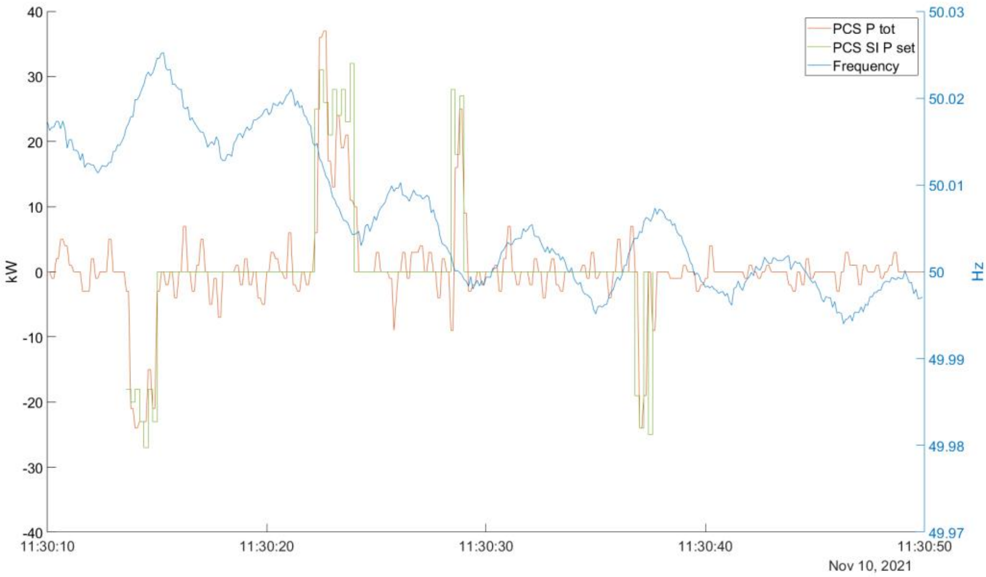


Figure 67: Behaviour of SI under low frequency oscillations

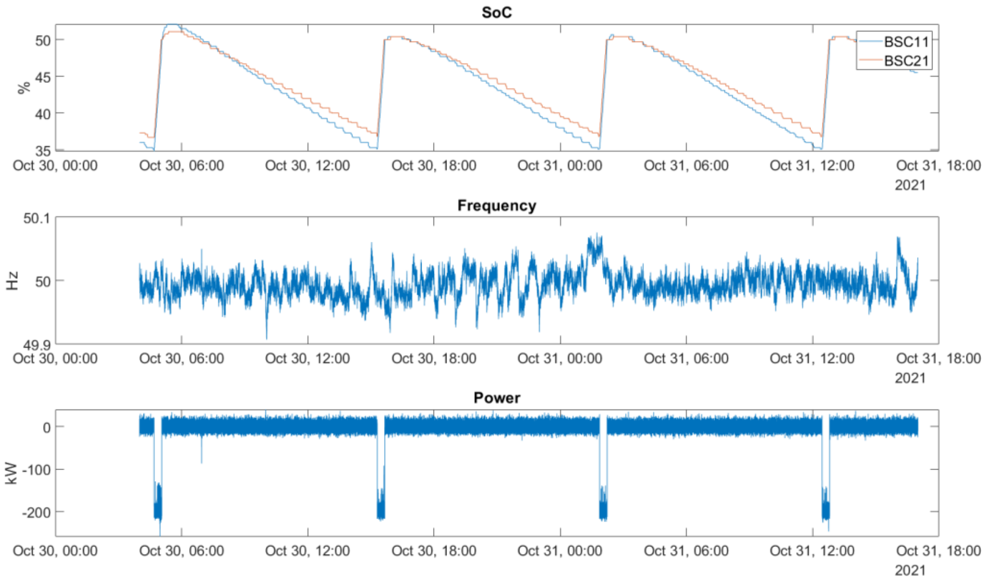


Figure 68: Evolution of SoC under SI and no major frequency deviations

- **Deterministic Frequency Deviations**

  The function DFD has also been tested during the field trials. Figure 69 depicts the response of the storage unit during a few hours on December 16th, where it can be observed how the system reacts to frequency deviations in both directions on an hourly basis, during a time window of 10 minutes. The function SoC restoration is also active, and will be triggered solely based on the SoC, independently of DFD. As it can be seen, in this case it interferes with the DFD function as a discharge of the battery is required when DFD is also active. Ideally these two functions would be coordinated to avoid this collision, which can be easily done by also implementing a time constraint on SoC restoration.

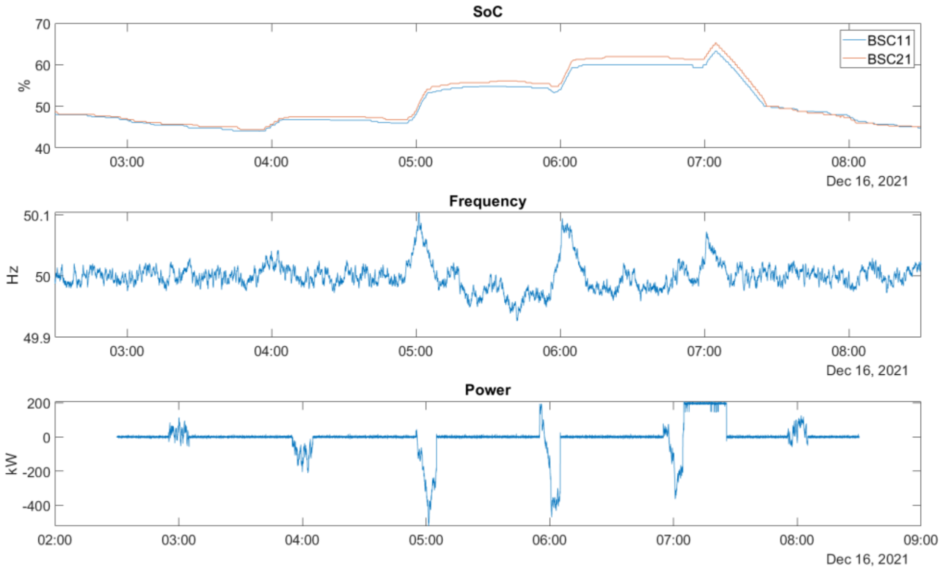


Figure 69: Behaviour of the DFD function and corresponding SoC evolution

7.9 Conclusions

Due to time constraints, the functionality has been tested for 3 months, during which no large event has been observed. Nonetheless, it was possible to assess the correct behaviour (i.e., according to specification) of the FCR+, EFR, SI and DFD functions, and its interactions with the SoC restoration that is always active in order to guarantee a proper SoC at any given time. The following has been observed in the test results:

- The parametric settings of the function have a large impact on the battery usage and its SoC.
- Whenever no large RoCoF is observed, SI barely provides power (as expected), but it can lead to small oscillations even for small RoCoF events. This could be avoided via reparametrization of the deadbands, but at the cost of making the function less sensitive and therefore less effective.
- Moreover, the actual magnitude of today’s deterministic frequency deviation leads to a frequent charging and/or discharging of the battery.

8 Future products for dynamic grid support

8.1 Introduction

The goal of work package WP6 is to derive recommendations for a future implementation of the fast control reserve concepts, which were developed and evaluated in previous work packages.

Besides the theoretical development of fast control reserve concepts, the question arises how they should be introduced in a power system. According to Figure 70, two general options exist to achieve the desired system behaviour.

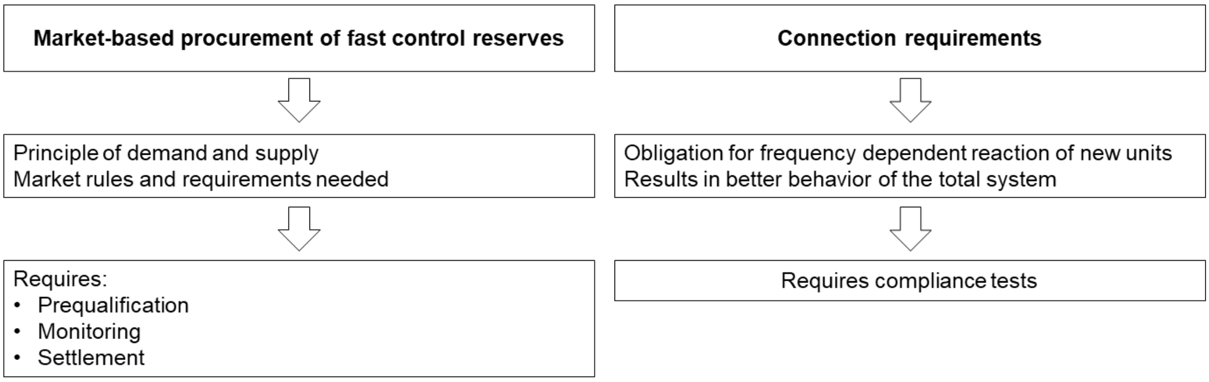


Figure 70: Options for the implementation of fast control reserves

The first option guarantees the desired system behaviour via a market-based procurement of fast control reserves – similar to already existing markets (e.g. for FCR). To organize a market, several aspects have to be considered, in particular the product design (maximum/minimum bid size, product period, conditional products, indivisible/divisible products, activation trigger, settlement, penalties, etc.), the prequalification of providers / reserve providing units (RPU) / technical entities (TE) and the monitoring of activation. Apart from that, the necessary regulatory framework (including respective market rules) has to be established. Experiences with existing control reserves have shown that such development processes require adequate time and comprehensive cooperation between the relevant transmission system operators (TSO) and stakeholders. For example, in case a new fast control reserve product is designed for an entire synchronous area (SA), TSOs need to compile several aspects, such as common technical requirements, dimensioning rules for the total required amount, allocation keys and possible restrictions for the distribution. Furthermore, market participants would most likely request TSOs to organize a single market for the entire SA, which introduces additional challenges (e.g. establishment of a central tendering/optimization platform, cross-border procurement and settlement, harmonization of boundary conditions, etc.).

While markets have the advantage that TSOs are able to constantly procure and monitor the necessary amount and quality of fast control reserves they may also introduce cost-inefficiencies, if the respective product design and remuneration system are not well suited. In addition, an illiquid market could potentially lead to operational challenges due to missing bids and hence insufficient amounts of fast control reserves.

To address these issues the second option is to mandatory require the necessary system behaviour (technical capability) from new and substantially modified RPU/TE. This can be achieved with the introduction of new or extended connection requirements in dedicated Connection Network Codes (CNC) [37] [38]. The implementation of this option might be easier, as it does not require additional market rules. However, an agreement on harmonized connection requirements for the entire SA is also a time-consuming task, which needs to be well organized. Within this context, the scope (size and/or technology of RPU/TE) and a general framework (trigger for activation, parameters for the activation itself, etc.) has to be first set up on a SA level and then specified in national grid codes. Besides, the current CNC legislation [37] [38] would also require the TSOs to validate the compliance of RPU/TE in the course of the connection process. Contrary to a market where the required behaviour may be organized by aggregation (pooling) of individual RPU/TE with different connection points, mandatory connection requirements can only be defined on the level of a single RPU/TE.

For all possible aspects, there is a need to consider a balance between the system needs, the capability of different technologies, the expectations from market participants and social welfare. Taking this into account, national or regional pilot projects, including TSOs, market participants, manufacturers and regulators, could serve as a promising basis to demonstrate the cost-efficiency and effectiveness of different fast control reserve concepts.

Similar to parallel developments in other SAs the following chapters of WP6 primarily focus on the implementation of fast control reserve concepts via technology-neutral products (market-based procurement).

Within this framework the results from the other work packages are combined with the following aspects, which are addressed and summarized in the next chapters:

- Market and technology potential analysis
- Parallel developments in other synchronous or control areas
- Technology neutral product definition
- Prequalification and monitoring
- Analysis of regulatory framework

8.2 Market and technology potential analysis

The current chapter focuses on the market potential of fast reserve market products in the Continental European (CE) power system. Starting with analysing the current situation the market potential of different future scenarios of 2030 and 2040 is investigated. These analyses aim to give a guidance for the development of new fast reserve market products. A graphical representation of the analysis flow and underlying methodology is given in Figure 71.

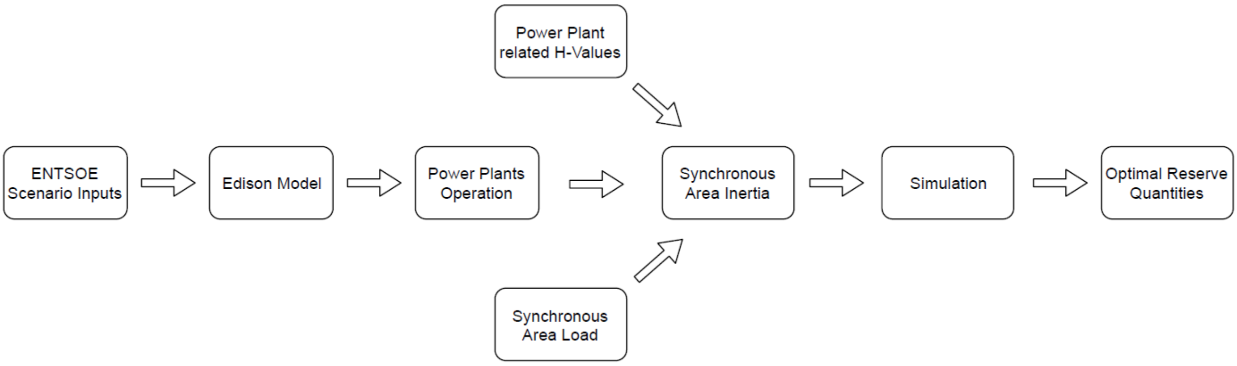


Figure 71: Analysis flow for determining the optimal reserve quantities

The market model EDisOn (Electricity Dispatch Optimisation), which is presented in section 8.2.1.2, calculates the operation of the power plants in the CE power system based on different future scenario inputs, illustrated in section 8.2.1.1.The power plant related inertia values (H-values) and the grid load are then considered to calculate the inertia of the CE power system as described in section 8.2.1.3. The necessary amount of the different fast control reserves is then calculated with a simulation model, which is described in section 8.2.2.2.

8.2.1 Methodology

In this chapter we present the scenarios considered in our analyses and the mathematical approach used for the calculation of inertia of the entire synchronous area. The scenarios are calculated with the EDisOn market model, described in section 8.2.1.2.

8.2.1.1 Scenarios

The reduction of overall greenhouse gas (GHG) emissions targets are the main incentive for the following scenarios. These reductions targets have been set by the European Union to achieve 80 – 95% GHG reduction in 2050 compared to 1990. The pathway of these emissions reduction [39] can be seen in Figure 72.

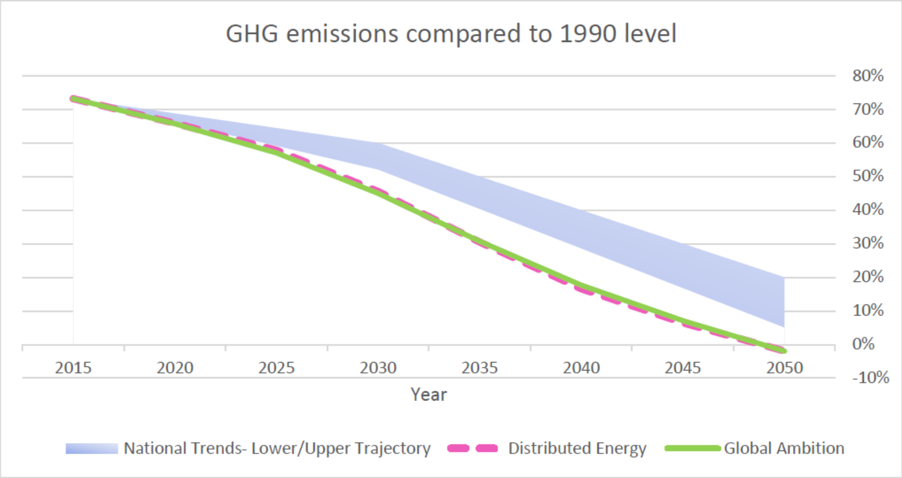


Figure 72: Decarbonisation pathways of the scenarios

Two different ENTSO-E scenarios, Global Ambition (GA) and National Trends (NT) are simulated, each for 2030 and 2040. The main inputs from these scenarios differ on specific political or social behaviour and decisions, regarding different technologies in both, private and industrial, environment. The six main parameters of the used storylines are listed in Table 11.

Global Ambition looks at a future that is led by large development in centralised generation including offshore wind and Power-to-X. It also considers a CO_2 budget.

The **National Trends** scenarios, are based on the National Energy and Climate Plans (NECPs) of all European countries. Therefore, this scenario is compliant with the national and EU targets on GHG emissions reduction, but not with a full decarbonisation.

Table 11: Key parameters of the used scenarios

	Global Ambition	National Trends
Macro-economic Trend	The focus is on centralised generation with cost reductions through economies of scale. A full decarbonisation till 2050 is implemented by using a CO_2 budget.	Climate policy is decided on a national level based on top-down European policy. Therefore, there is a moderate growth in many sectors caused by financial reasons.
Transport	Zero-emission transport is a key component and therefore there is a high penetration of electrical vehicles. Heavy good vehicles use green gas, and other CO_2 neutral fuels.	Share of electrical and hybrid vehicles grows moderately as well as internal combustion engines using green gas for heavy good vehicles.

Residential	Fossil fuels are completely replaced by heat pumps and green gas.	Energy efficiency improvements lead to a lower heat demand. A variety of heating solutions is implemented based on regional climate specifications. New buildings are heated to a high extend with heat pumps, but there are still many gas-fired appliances.
Industrial	Fossil fuels are replaced by green gases and electrification. Carbon storages are in use and the overall energy demand is reduced, through higher energy efficiency.	Energy efficiency in balance with economic growth leads to a stable industrial energy demand.
Electricity	RES-E is competitive without subsidies, that leads to a high share of PV devices in Southern Europe and high share of wind farms in Northern Europe. There are nearly any new nuclear power plants while existing ones are decommissioned based on national plans. Gas fired power plants use green gas and carbon storages.	Investment decisions are done on national level, but overall a high share of electricity generation is done by wind and solar. Generation is typically done in a centralised way, since decentralised energy is limited to those who can afford it. Gas fired generation replaces coal and to a certain level nuclear generation.
Gas	CO_2 neutral gases substitutes natural gas.	Natural gas is still dominant. Power-to-Gas is mainly used for energy storage reasons but not for supply.

8.2.1.2 EDisOn – Energy Market Model

To analyse and quantify the usage of power plants, and in further consequence calculate the H – values in the future scenarios, the energy market model EDisOn is used. This tool, developed by the Energy Economics Group - TU Wien, has already proven its benefits in various national and international projects and several studies. It was used to analyse Austria's transmission grid extensions [40], the energy efficiency targets [41], the climate strategy targets of Austria [42], the effects of future balancing market designs [43] and the future challenges for hydro power [44].

This model for power plant operation simulates the electricity wholesale and balancing market for 25 countries within the CE power system (see
Figure 73). Whereby the power exchange between 13 of these countries (AT, BE, CH, CZ, DE, FR, HU, IT, NL, PL, SI, SK, LU) is calculated by a DC load-flow approximation approach, the

remaining 12 countries of the SA (AL, BA, BG, DK, ES, GR, HR, ME, MK, PT, RO, RS) are implemented by using their interconnectors' net transfer capacity (NTC) limitations.
The market simulations are based on a 380-kV backbone for 2030, considering the simulated CE power system. This grid model makes a cost optimised, cross-border generation simulation possible. Additionally, the 220-kV grid within Austria is considered. Based on a DC load flow/NTC approach the optimal electricity generation schedules as well as the usage of renewable energies and storages are calculated. Subsequently, the rotating masses in operation and the respective H-values can be calculated. The mathematical formulations of the EDisOn model can be found in [45].
The model is deterministic and presumes a perfectly competitive market approach with perfect foresight. It has a 60-minute time frame resolution and can be solved for a whole year or as a rolling-horizon optimisation based on country level or on control area level. The model results in a cost-minimal electricity generation dispatch for a given area and time considering a system-oriented cost optimal balancing capacity procurement. The FCR and FRR capacity procurement is implemented based on an opportunity cost approach, i.e. determining the opportunity costs of shifting capacity from the wholesale to the balancing market.

Constraints for wholesale electricity market simulation:

- Demand for electricity and heat must be met by supply
- Capacity constraints of power plants
- Thermal coupling of thermal plants is used for thermal demand; additionally, power to heat is possible
- Start-up costs, ramping limits (up and down) of thermal power plants
- Storage level equations of pumped hydro storage and hydro storage plants
- Storage level of pumped hydro storages have to follow an annual pattern (realistic operation)
- RES-E curtailment (PV, wind, natural inflow of hydropower)
- Transmission grid model with a DC load flow or NTC approach
- Transmission line limitations by their NTCs
- Procurement of Balancing energy

The procurement of different types of balancing products (FCR, aFRR and mFRR) is implemented into the model before the optimal power plant dispatch is calculated. Balancing energy procurement, and therefore the guaranteed balancing capacity influences the remaining available capacity of the generation facilities on the energy market. The activation of this balancing energy is not a part of the model.

Figure 73: Simulated countries within the EDisOn energy market model

8.2.1.3 Calculation of the H-Values

Inertia in power systems is determined by considering all the rotating masses directly connected to the electrical grid. From a formal point of view, the H-Value [s] represents the inertia of an investigated system. It is related to the time constant of the network T_A which is defined as follows:

$$H = \frac{T_A}{2} \qquad (3.1)$$

In order to estimate the overall system inertia within the CE power system, different calculation steps are carried out. In the first calculation step, an hourly weighting factor $w_i(t)$ is assigned to each of the n different generation types. This factor represents the percentage quantity of generation of the technology i within the CE power system. Thus, the weighting factor $w_i(t)$ in a system with n generation types is defined as follows:

$$w_i(t) = \frac{S_i(t)}{\sum_{i=1}^{n} S_i(t)} \qquad (3.2)$$

Moreover, each generation type is characterized by an inertia constant (H_i) and a loading factor LF_i, which are used to estimate the overall system's inertia. Typical inertia constants and loading factors for some representative generation types are summarized in Table 12.

Table 12: Typical inertia constants and loading factors for some representative generation types

Generation type	Inertia constant H_i	Loading factor LF_i
Nuclear	5.9 s	0.96
Fossil Coal	4.2 s	0.7

Fossil Gas	4.2 s	0.6
Run-of-River	2.7 s	0.61
Hydro Pumped Storage	3.5 s	0.46
Solar/Wind	-	-
Biomass	3.3 s	0.7

Considering a group of n generation types, the total system inertia $H_{sys}(t)$ and kinetic energy $E_{sys}(t)$ for each hour can then be calculated as below.

$$H_{sys}(t) = \sum_{i=1}^{n} \frac{H_i \cdot w_i(t)}{LF_i} \quad (3.3)$$

$$E_{sys}(t) = H_{sys}(t) \cdot \sum_{i=1}^{n} S_i(t) \quad (3.4)$$

8.2.2 Market potential analysis

8.2.2.1 Comparison between the present scenario (2017-2019) and future scenarios (2030 and 2040)

To achieve our goals, it is essential to analyse the present and future inertia in the CE power system for multiple scenarios. Figure 74 shows the annual duration curves of the H-Value for the years 2017-2019 and for different future scenarios.

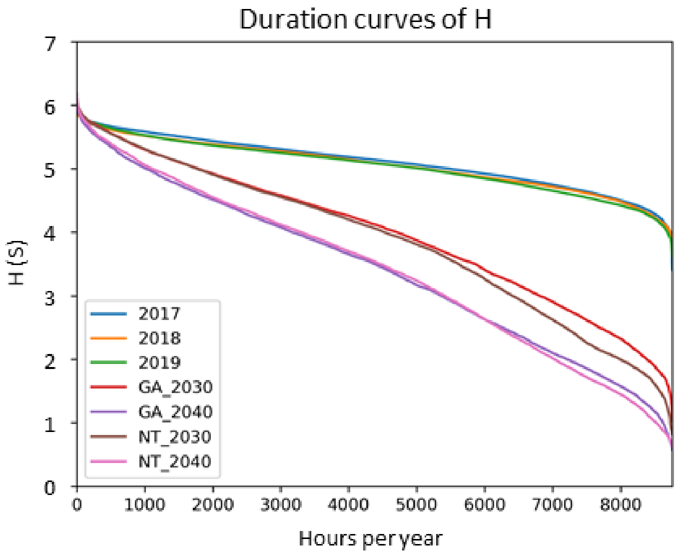


Figure 74: Annual duration curve of the H-value

As we can observe, the H-Values in the future scenarios are lower than those of the years 2017 to 2019, which vary mostly between 5 s and 6 s. In this section we will mainly show the analyses of one representative future scenario (GA 2030). In Figure 74 it can be observed how the slope of the GA 2030 scenario duration curve is much more prominent than that of the years 2017 to 2019. This indicates a greater variability of the inertia of the electricity grid caused by the increase of renewable inverter based generation. This effect is even more visible when the daily and seasonal distribution of the inertia during a year is analysed. The H-Value distribution in the years 2017 to 2019 and in the GA 2030 scenario is shown in Figure 75.

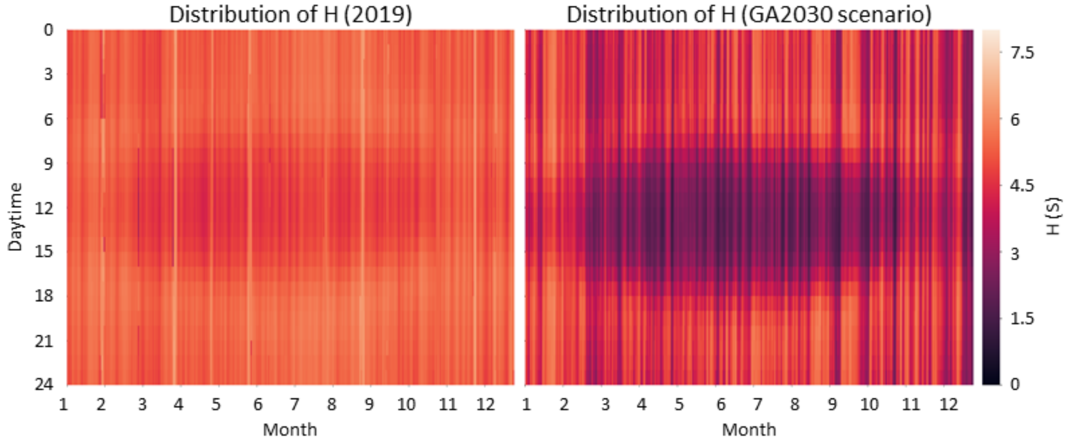


Figure 75: Value distribution in the years 2017 to 2019 and in the GA 2030 scenario

In the graph representing the distribution of the H-Values in the years 2017 to 2019, a dark area in the centre is slightly visible, which is mainly caused by the production of electricity from PV. With the increased installation of PV based generation in the CE power system, this daily and seasonal effect becomes much more evident in the scenario GA 2030. This causes a high variability of the inertia, which must be counteracted with adequate measures for maintaining the frequency stability. In the following Figure 76, it is possible to observe the change of the average H-Value in the individual countries in the years 2017 to 2019 and in the GA 2030 scenario.

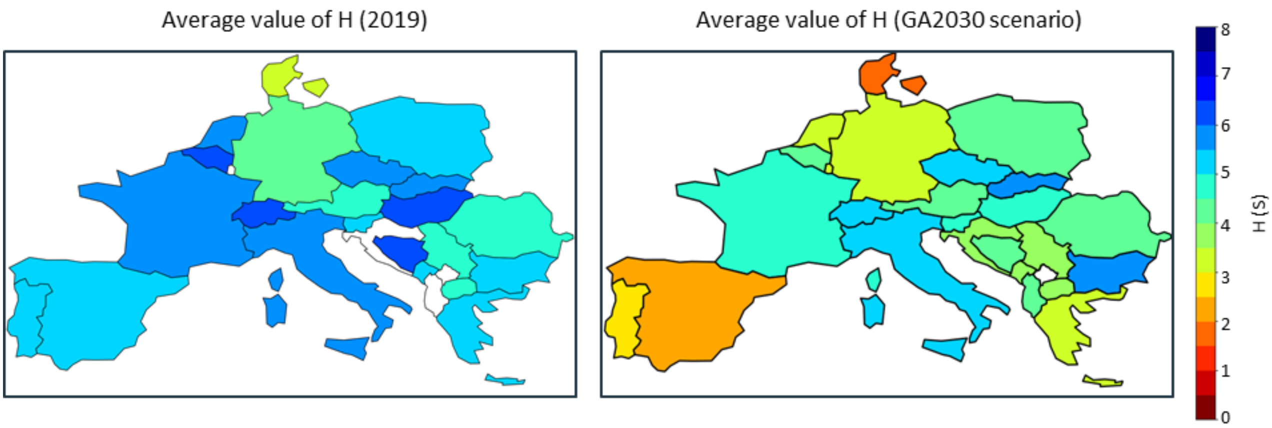


Figure 76: H-Value in the individual countries in the years 2017 to 2019 and in the GA 2030 scenario

It is possible to point out that in the GA 2030 scenario most countries have a reduced H-Value compared to 2017 to 2019. In addition to France and Italy, only various Eastern European countries have an average H-Value higher than 5 s. Denmark, Greece, Germany, Holland and

the entire Iberian peninsula have an average H-Value between 2 s and 3 s. For Denmark, Germany and Holland this is due to the installation of wind turbines, while in the case of Spain, Portugal and Greece this is due to the installation of PV based generation. France, according to the GA 2030 scenario, will still cover a large part of its load with nuclear power plants, which serve as a “backbone” for the inertia in the system. Italy will produce a large part of hydroelectric energy in the GA 2030 scenario. Hydroelectric plants, being rotating generators, also contribute to the inertia of the electrical grid.
However, the inertia levels of the countries with the highest generation and consumption have the greatest impact on the total inertia in the CE power system. Figure 77 summarizes the rotational energies of the major inertia contributors, namely France, Germany, Italy, Spain and Poland.

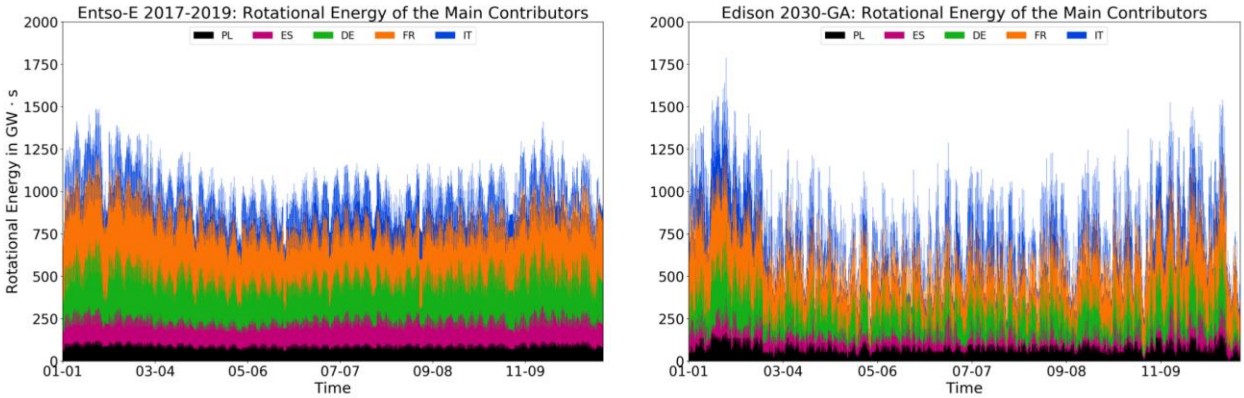


Figure 77: Rotational energies of the major inertia contributors of the CE power system in the year 2109 and the GA 2030 scenario

It is observable that from 2017 to 2019 each country provides much more constant rotational energy than in the GA 2030 scenario. Particularly Germany (green) presents a high variability of rotational energy in the GA 2030 scenario, due to the high shares of inverter based generation. On the other hand, France (orange) retains a part of the constant rotational energy supplied by nuclear power plants.

8.2.2.2 Quantitative Analysis

Development of the future design hypothesis

The estimations of the future inertia constant in the CE power system, shown in the previous section, clearly indicate the need of adequate mitigation measures to ensure frequency stability. This subsection shows the necessary amounts of fast control reserves for the years 2030 and 2040.
Table 13 shows the main assumptions for the dimensioning cases (future design hypothesis) of the different fast control reserve concepts. The power imbalance is equal to the CE reference incident of 3 GW, as it is already defined in the System Operation Guideline [11].]. In contrast to the scenarios based on the classical design hypothesis (chapter 5.2), the remaining parameters (system load and self-regulation effect of loads) are also changed as a result of the EDisOn market model simulations for the future design hypothesis. The values of the

system load, inertia constant, self-regulating effect of loads and behavior of conventional FCR are chosen under the following assumptions:

- Increase of system load (sector coupling, EVs, heating pumps, etc.)
- Decrease of H-value (increasing share of inverter based generation)
- Decrease of self-regulating effect of loads (increased share of inverter based motors/loads)
- Linear activation of FCR based on the current minimum requirements (full activation within 30 s)

Table 13: Future design hypothesis parameters

Parameter	**Status quo**	**2030**	**2040**
Power imbalance	± 3000 MW	± 3000 MW	± 3000 MW
System load	150 GW	200 GW	225 GW
Self-regulating-effect of the loads	1 %/Hz	1 %/Hz	0,75 %/Hz
H-value	2,5 s	1,5 s	1,0 s

<u>Simulation results</u>

Figure 78 and Figure 79 show simulated frequency curves for a simplified model of the CE power system, considering the future design hypothesis parameters and solely activating conventional FCR. It can be seen that the simulated frequency in 2030 drops below the dynamic security limit of 49.2 Hz, if no other emergency functionalities of the power system, such as shedding of industrial loads or pumps above 49 Hz, are active. In the year 2040 the simulated frequency drops below 49 Hz, which is the current limit for load shedding in the CE power system. Since such values of the network time constant are likely to occur in the future, mitigation measures such as fast control reserves should be considered.

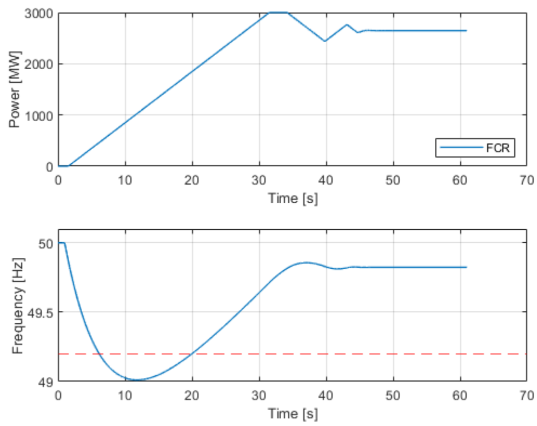


Figure 78: Design hypothesis 2030 without fast control reserves

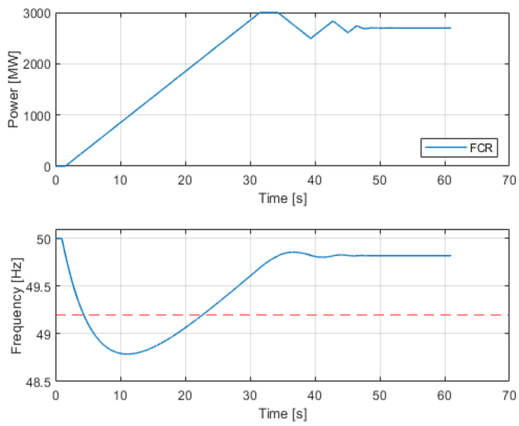


Figure 79: Design hypothesis 2040 without fast control reserves

The corresponding demands for fast control reserves, in order to keep the frequency above the dynamic security limit of 49.2 Hz, are summarized in Table 14. Exemplary activations of FCR+ can be seen in Figure 80 and Figure 81.

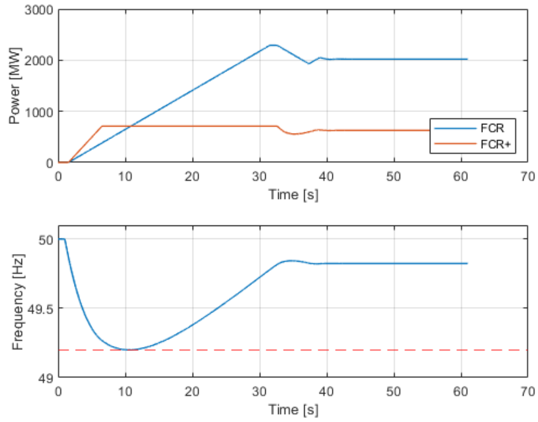


Figure 80: Design hypothesis 2030 including FCR+ to keep the frequency ≥49,2 Hz

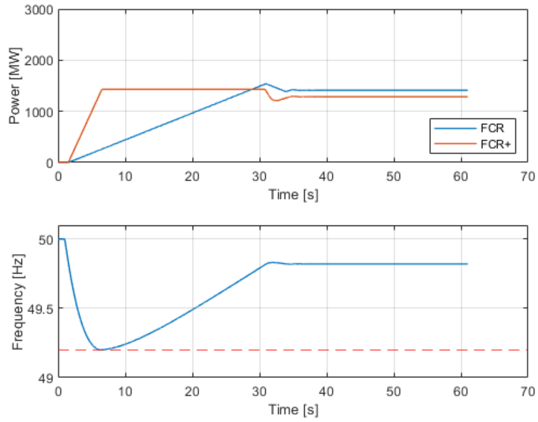


Figure 81: Design hypothesis 2040 including FCR+ to keep the frequency ≥49,2 Hz

As can be seen in Table 14, the necessary amounts of fast control reserves significantly differ between the scenario years 2030 and 2040. Put simply, the respective amounts approximately double between 2030 and 2040. This high increase can be mainly explained by the further decrease of the self-regulating-effect of the loads and inertia, which subsequently leads to more severe frequency drops in the first seconds following an imbalance. The results in Table 5 furthermore show, that the highest amounts are generally needed for SI in both 2030 and 2040. These high amounts can be justified by the rather short RoCoF-based activation of SI compared to the duration of frequency recovery process. Compared to EFR and FAPI the demand for FCR+ is slightly higher in 2030 since FCR+ would replace a part of FCR, while EFR, FAPI and SI would be considered as an additional control reserve to the current FCR.

Table 14: Necessary amounts of fast control reserves

Parameter	2030	2040
FCR+	710 MW	1430 MW
EFR	620 MW	1500 MW
SI	1190 MW	2680 MW
FAPI	560 MW	1190 MW

8.2.3 Technology potential analysis

This section presents the results of the technology potential analysis, which aims at assessing the suitability of different technologies for providing the different fast control reserve concepts. In order to qualitatively assess the suitability a number of different aspects are taken into account. These aspects include the full activation time, the potential duration of provision and further aspects, like wear of components or the capability of symmetrical provision. The results of this analysis are summarized in Table 15.

Table 15: Technology potential analysis

Technology option	Suitability FCR+	Suitability EFR	Suitability SI	Suitability FAPI
Nuclear	less suitable	possibly suitable	Inertia certificates	not suitable
Coal	less suitable	possibly suitable	Inertia certificates	not suitable
Gas	less suitable	possibly suitable	Inertia certificates	not suitable
Run-of-River	less suitable	possibly suitable	Inertia certificates	not suitable
Pumped storage				not suitable
- *Synchronous generator*	possibly suitable	possibly suitable	Inertia certificates	not suitable
- *Full-size converter*	possibly suitable	possibly suitable	possibly suitable	not suitable
- *DFIG*	possibly suitable	possibly suitable	Inertia certificates	not suitable
Photovoltaics	not suitable	not suitable	possibly suitable	possibly suitable
Wind	not suitable	not suitable	possibly suitable	well suited
Battery system	well suited	well suited	well suited	well suited
Flywheel	not suitable	less suitable	well suited	well suited
Supercaps	less suitable	less suitable	well suited	well suited
Controllable Loads	less suitable	well suited	less suitable	well suited

Legend
well suited
possibly suitable
less suitable
not suitable
Inertia certificates

As shown in Table 15 traditional power plants (nuclear, coal, gas and run-of-river plants) are possibly suited for providing EFR but less suitable for providing FCR+. These power plants are connected to the grid via synchronous generators and provide inertia inherently. Consequently, these plants do not need to provide SI but could possibly monetize their inherent inertia, via inertia certificates. Finally, these plants are not suitable for providing FAPI, since this would deteriorate their dynamic response and would lead to undesirable behaviour. The considerations regarding FAPI also apply for pump storage plants. Contrary to the other traditional power plans, pump storage plants may be more suitable for providing FCR+. However, turbine controller tuning and the wear of components still have to be taken into account. Furthermore, pump storage plants connected via full-size converters cannot provide inertia inherently but are possibly suitable to provide SI.

Photovoltaics and wind turbines generally fulfil the necessary requirements regarding the response time and full activation time. However, since these rely on the available wind and solar power, they can only provide continuous or longer frequency responses at rather short and unpredictable timeframes. Consequently, photovoltaics or wind turbines without an additional energy storage may not be suited to provide FCR+ and EFR, particularly not symmetrically. This is due to the fact that photovoltaics and wind turbines will be most likely unable to increase active power, unless they are intentionally operated with reduced power. On the other hand, both photovoltaics and wind turbines might be more suited to provide SI or FAPI as these functions are only activated for rather short timeframes and additionally require a very low E/P-ratio.

Battery systems are well suited to provide all of the fast frequency responses if dimensioned accordingly. Flywheels and Supercaps, on the other hand, are less suitable or not suitable to provide FCR+ or EFR because of their limited capacity. Finally, controllable loads are well suited to provide EFR and FAPI, particularly asymmetrically. Since controllable loads might be also used for other (industrial) processes they may not be suitable to provide continuous frequency responses as it is the case for FCR+. Furthermore they are less suitable for providing SI because of their limited resolution for quickly adjusting power.

8.3 Parallel developments in other synchronous or control areas

One important part of this work package was the exchange of experiences with other European TSOs who have already begun to address the issues related to the future decrease of inertia in their SA. The information gained in this exchange of experience also supported the considerations regarding the technology neutral product definition, which is discussed in section 8.4. The main aspects of the exchange of experience are briefly summarized in section 8.3.1.1. Additionally, section 8.3.1.2 shortly describes a new balancing product from the Italian TSO TERNA that is expected to be implemented in 2022. Furthermore, the collected data are resumed in the table in section 11.1.

8.3.1.1 Exchange of experiences with National Grid (UK) and Nordic TSOs.

National Grid

In recent years the TSO National Grid has developed a new fast control reserve called “Dynamic Containment” (DC) for the UK power system. It is planned to release DC as the first of new end-state products, in order to meet the most immediate need for faster-acting frequency response. The product is designed to operate post-fault, i.e. for deployment after a significant frequency deviation.

Nordic TSOs

In parallel the TSOs of the Nordic power system have developed a product called “Fast Frequency Response” (FFR). FFR as a new static product is deemed the most promising mitigation measure for low inertia situations since several technologies can provide fast active power response estimated at low socio-economic costs. According to the feasibility study, FFR is a more cost-efficient measure for handling low inertia challenges compared with reducing the size of the reference incident or procuring more existing reserves (FCR-D).

Differences between DC (UK) and FFR (Nordic)

While both DC and FFR are designed to operate very fast in case of significant frequency deviations they have some significant differences. One important difference is that DC is activated proportionally to the frequency deviation, while the activation in the case of FFR is static. Another difference is that DC is currently classified as a symmetric product and FFR as an asymmetric (underfrequency) product only. In both cases, each RPU/TE must pass the technical prequalification. With regards to the performance monitoring, market participants in the DC market must additionally provide their baseline, which usually reflects the schedules. However, in the case of FRR a concept for the baseline has not yet been defined. The necessary amount of DC and FFR both depend on a dynamical dimensioning approach because the volumes are highly dependent on the reference incident and other key factors such as renewable forecasts. In the DC market the auctions are scheduled every week while in the Nordic Power system the auctions are either organized on a daily (Finland) or monthly (Sweden and Norway) basis. Furthermore, in the DC market, the provider's remuneration is calculated considering the availability/unavailability and a service performance measure. The remuneration systems in the Nordic countries differ slightly from each other, but are mostly based on a marginal pricing concept of the offered power. A future prospectus is a common FFR market in all Nordic countries.

8.3.1.2 Other developments

Currently the Italian TSO Terna is developing a balancing product called "Fast reserve" (FR). Terna justifies the need to define this fast control reserve to manage the progressive reduction of inertia and the specific needs of the Italian grid. However, it has to be noted that this control reserve is not coordinated on the CE SA-level and is not intended to replace the share of conventional FCR in Italy. The main idea of FR is to provide a fast additional frequency proportional response in case of frequency deviations. A full activation of FR has to be performed within 1 second and maintained for 30 seconds, until the conventional FCR is fully activated.

The auction to participate to the FR-market will be organised yearly and is based on the power price. The remuneration of the power is the pay-as-bid approach, while the energy is remunerated with the day-ahead spot market price. The market participants are currently signing for a 5 years contract. They accept to make the FR-power offered available for 1000 hours per year. In this regard, Terna publishes an initial estimate of the hours of availability for the following year by the end of each year. Subsequently, two days in advance, Terna communicates the precise hours in which to guarantee availability. This methodology allows a long-term planning of investments and energy consumption, which could make this market more attractive.

8.4 Technology neutral product definition

Within this chapter the procurement of the fast control reserve concepts EFR, FCR+, SI und FAPI on balancing markets was consistently evaluated with market criteria, taking into account various implementation scenarios. The selected market criteria and implementation scenarios are described in section 8.4.1. The results of the market evaluation are summarized in section 8.4.2.

8.4.1 Market criteria and implementation scenarios

8.4.1.1 Market integration

Market integration analyses, if it is possible to create consistent market areas with collective goals, time schedules and product requirements to realize synergy effects from existing markets, processes, platforms and products.

8.4.1.2 Market liquidity

To achieve a high Market liquidity it is beneficial to establish a level-playing-field, which is widely independent from used technologies and offers enough financial incentives compared to other markets.

8.4.1.3 Market entry

Market entry depends on requirements for prequalification and service-quality as well as product complexity, process costs and automation. Therefore simple product definitions are useful (e.g. few time slices, small minimum bid size and long auction intervals). Profitable market participation for smaller providers can be secured by minimum IT-requirements, while providers with bigger transaction volumes can be supported by optional IT interfaces.

8.4.1.4 Price rating

The price rating compares cost components (investment, fixed costs, variable costs, opportunity costs and price risks) to potential earnings from a providers point of view. For existing plants the market prices must at least cover all cost components, while new plants are only constructed, if estimated earnings clearly exceed investment costs.

8.4.1.5 Market rules

Generally simple market rules facilitate market entry and reduce process costs. Therefore auction markets are preferred to labor-intensive flow markets and if possible, only one product should be traded (namely options, certificates or energy). High bid volumes presupposed, pricing is easier with marginal-pricing then with pay-as-bid.

8.4.1.6 Description of implementation scenarios

The following implementation scenarios for the fast control reserve concepts were used:

Table 16: Description of implementation scenarios

Product	Base scenario (…/B)	Alternative scenario (…/A)
EFR	Procurement with <u>symmetric</u> products analog to existing control reserve products	Procurement with <u>asymmetric</u> products analog to existing control reserve products
FCR+	Procurement within the framework of the existing FCR market	No alternative scenario defined

SI	Procurement with symmetric products analog to existing control reserve products	Inertia certificate trading
FAPI	Procurement with symmetric products analog to existing control reserve products	Procurement with asymmetric products analog to existing control reserve products

8.4.2 Market evaluation

This chapter briefly describes the key findings from the market evaluation with the selected market criteria and implementation scenarios. More details (detailed evaluation of sub-criteria) can be found in Annex 11.2.

Table 17: Summary of market evaluation

Market criteria	EFR/B	EFR/A	FCR+/B	SI/B	SI/A	FAPI/B	FAPI/A
Market integration	1,7	2,0	1,0	2,3	2,3	2,3	2,3
Market liquidity	1,7	1,3	1,3	2,3	1,3	2,3	1,7
Market entry	1,5	1,3	2,3	2,8	2,3	2,3	2,0
Price evaluation	2,5	2,0	2,0	2,0	2,0	1,5	2,0
Market rules	2,0	1,7	1,0	3,0	1,3	2,0	1,3
TOTAL	1,9	1,7	1,5	2,5	1,9	2,1	1,9

Highly applicably	1
Possible applicably	2
Less applicably	3
Not applicably	4

8.4.2.1 Enhanced Frequency Response (EFR)

The good overall rating of EFR results from easy market entry for various providers and technologies as well as an expectable high market liquidity. EFR could be a suitable alternative for many technical facilities, which cannot take part in other flexibility markets. In case of asymmetric product design (EFR/A) even controllable or switchable loads could be used. Due to rare EFR activation the auction periods could be longer (monthly or yearly) and the monitoring could be executed ex-post, which would minimize the amount of work for providers and TSOs. EFR is designed for high frequency deviations in case of severe imbalances and would not improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Therefore, EFR has to be procured additionally to existing FCR and depending on the applied technology, option prices could be relatively high compared to its infrequent activation.

8.4.2.2 Frequency Containment Reserve Plus (FCR+)

FCR+ could be procured as part of existing FCR auctions, which would open up many synergies. The FCR+ price level is expected to be above FCR prices and thus would lead to sufficient market liquidity.
Due to its fast response characteristics FCR+ would additionally improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Furthermore, FCR+ could be an interesting alternative for RPU/TE, which already take part in FCR auctions. However, due the higher technical requirements regarding the dynamics and monitoring only larger and highly flexible RPU/TE would be able to enter into FCR+ markets.

8.4.2.3 Synthetic Inertia (SI)

Due to the complexity of the concept of SI, certificate trading appears to be more advantageous than a tender concept via a symmetrical product design. This would also ensure a fair balance between technologies, which inherently provide inertia (e.g. synchronous generators) and specifically adapted systems (e.g. batteries). SI has to be procured additionally to existing FCR and the setup of this new certificate market would naturally require substantial efforts in trading and monitoring processes. On the other hand inertia certificates will likely generate high market liquidity and SI would additionally support the frequency stability. Further details regarding the potential implementation of inertia certificates can be found in [46].

8.4.2.4 Fast active power injection (FAPI)

Because of its simple technical requirements FAPI could be an alternative for many RPU/TE, which cannot take part in other flexibility markets (e.g. wind turbines or heat pumps). However, its static and uncontrolled activation requires additional care for the determination of the appropriate (individual) trigger and the regional distribution of participating RPU/TE, to ensure (local) system stability. Due to rare FAPI activation the auction periods could be longer (monthly or yearly) and the monitoring could be executed ex-post, which would minimize the amount of work for providers and TSOs. FAPI is designed for high frequency deviations in case of severe imbalances and would not improve the frequency stability within the typical operation range 50 +/- 0,2 Hz. Therefore, FAPI has to be procured additionally to existing FCR and depending on the applied technology, option prices could be relatively high compared to its infrequent activation.

8.5 Prequalification and monitoring

A market-based procurement of fast control reserves requires prequalification of the participating RPU/TE and a monitoring of the provided service. In this section basic aspects concerning technical prequalification (PQ) and monitoring of high dynamic reserves are discussed. Technical PQ means a process within which the compliance of a potential provider with the reserve requirements is checked. A positive PQ is the basis for participation in the market. Usually it is accompanied by a contractual agreement, which e.g. regulates accounting aspects or procedures in case of non-sufficient reserve activation. The principles for PQ and monitoring are based on experience with existing reserves in the CE power system (FCR), the exchange of experience with other EU TSOs and the results of the analysis made in the course of the practical tests conducted in WP4 and WP5.

8.5.1 Basic PQ-requirements

8.5.1.1 Pooling of Technical Entities

A fundamental aspect is the general decision upon possible pooling concepts. In general, pooling opens the opportunity for optimization of provision and activation of reserves between individual RPU/TE. By applying a pooling concept providers have to fulfil the respective reserve requirements not necessarily with each individual RPU/TE, but only with their pool.
For the provision of highly dynamic reserves the efforts on coordination, data provision and monitoring will increase. It might appear too complex and costly to coordinate such reserves in a large number of small TE. In particular the amount of data needed for monitoring could be seen as an obstacle for small RPU/TE. Moreover, a central control of distributed RPU/TE might create an unacceptable time delay due to the data transmission considering the required full activation time. Therefore, the application of pooling concepts might be limited to larger units.

8.5.1.2 Participating Technical Entities - Operational Concept

In the course of the PQ the potential provider has to explain

- Which RPU/TE will participate (technology, technical features like possible ramp rates, limited reservoir, data interface, etc.),
- The baseline concept,
- In case of a pooling concept: operational coordination of the participating RPU/TE,
- Possible additional services, which might be offered in parallel.

The requested information has to include also an availability- and self-monitoring-concept.

8.5.1.3 Frequency Measurement

Frequency Measurement is the fundamental basis for any frequency depending reserve activation. Thus, both time resolution and measurement accuracy are of specific importance. In general local frequency measurement at the site of the RPU/TE is considered necessary irrespective of whether or not the involved RPU/TE constitute a pool.
Taking into account the preliminary conclusions from chapter 5.6.1 the following requirements are recommended for all investigated fast control reserve concepts:

- Sampling rate for frequency: 100 ms
- Measurement accuracy for frequency: ≤ 10 mHz

For SI a robust measurement of the RoCoF is of outstanding importance. Nevertheless, a compromise has to be found. On one hand incorrect measurements due to frequency variations and respective overreactions have to be avoided. This can be reached by means of filters and larger measurement windows, which inherently introduce time delay effects depending on their parameters. On the other hand SI has to react very quickly to be able to emulate a real inertial response. Based on a detailed analysis the following requirements for determination of RoCoF are recommended by assuming an initial delay for SI < 0,5 s and a measurement accuracy ≤ 10 mHz/s:

- Block-shaped time window of 300 ms length as an acceptable compromise (see Figure 82)
- Frequency filtering by means of a low pass filter with low order to avoid unacceptable time delays

Since the RoCoF highly depends on the chosen measurement location and concept, the calculated value of the RoCoF, which is used for the respective SI activation must be available for a separate correctness check.

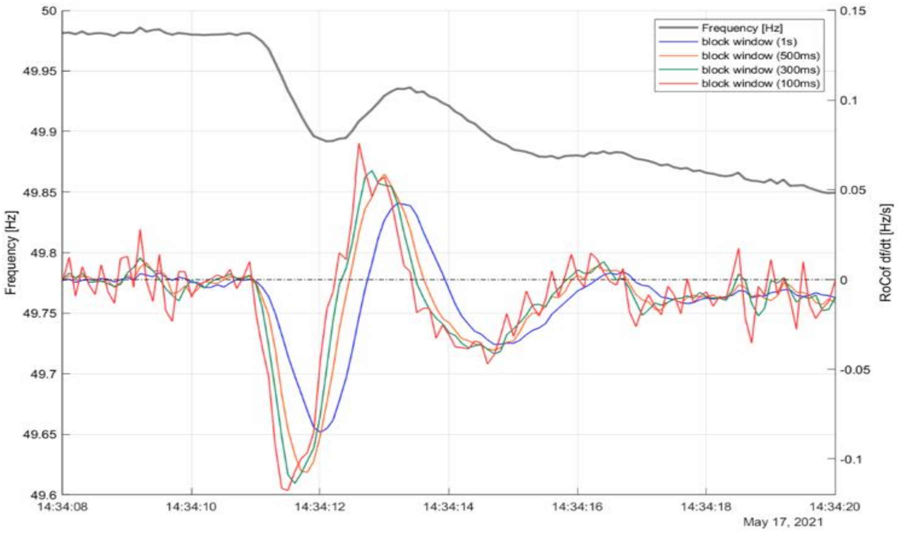


Figure 82: Comparison of different sizes of the block window

8.5.1.4 Measurement of active power

For the measurement of active power it has to be distinguished if the service is activated continuously (FCR+) or triggered only in specific endangered situations, like extra-ordinary system imbalances. For discontinuous services lower accuracy of measurements could be acceptable.

For FCR+ an accuracy class of measurement transformers of 0,2-0,5 depending on the ratio of guaranteed reserve power to rated power is recommended to allow for clear verification of activation. In case of non-compliance overfullfillment of activation might be acceptable to compensate possible measurement errors.

8.5.1.5 Baseline concepts

For currently existing reserves the up-to-date verification approaches require the determination of a baseline as a reference power. Consequently, the baseline will be needed for FCR+.

Regarding SI, EFR and FAPI it might not be required as activation is only triggered in specific cases for a short time period where a simultaneous and similar fast baseline change is unlikely. In general the field tests support the approach of neglecting the baseline if a simultaneous change of the baseline is unlikely, the required response time is very short and the sampling rate for the monitoring is correspondingly high.

8.5.1.6 Functional test

The provider has to ensure that each TE – or respectively the pool - which contributes to a specified service comply with the respective requirements. Thus, a functional test of the TE respectively of a pool of TE (depending on the applied concept) will be necessary to verify both technical compliance and data communication with the TSO. The functional test should consist of a:

- Standard step response test (double or triple step)
- Standard frequency profile response
- Duration test (energy capability)

A determination of the boundary conditions - like step height or applied frequency profile - and respective compliance ranges for the measurements will be needed to ensure non-discriminatory treatment.

8.5.1.7 Performance Monitoring

For FCR+ the transmission of real time online data per provider (time resolution of 1 s; similar to FCR) should be required. For EFR, SI and FAPI online data could be too complex in relation to the expected benefit – for EFR and FAPI due to their discontinuous (and probably rare) activation and additionally for SI due to the high sampling rate needed. Apart from that for all considered reserve types archived data for ex-post analysis should be available with a time resolution of 100 ms for a time period of at least 8 weeks. It is recommended to transmit or respectively archive at least the following data:

- Frequency
- In case of SI: the internally calculated value of RoCoF, which is used for the respective activation
- Baseline (if required for the reserve type)
- Active Power

Verification should be done by checking if the activation respects determined acceptance ranges. This can be reached by directly comparing the time series of activation with the time series of these ranges. For continuous services, namely FCR+, additionally statistic methods could be applied, e.g. a check of the overall slope of activation. Respective data analysis in the course of the field tests (Figure 83) showed that such analysis of the slope could be sufficient, assuming that the activation immediately follows the new set point. Taking this into account the effect of a possible time delay on the correlation is negligible. If necessary an additional monitoring of time series of activation could be applied, in order to check the dynamic behaviour.

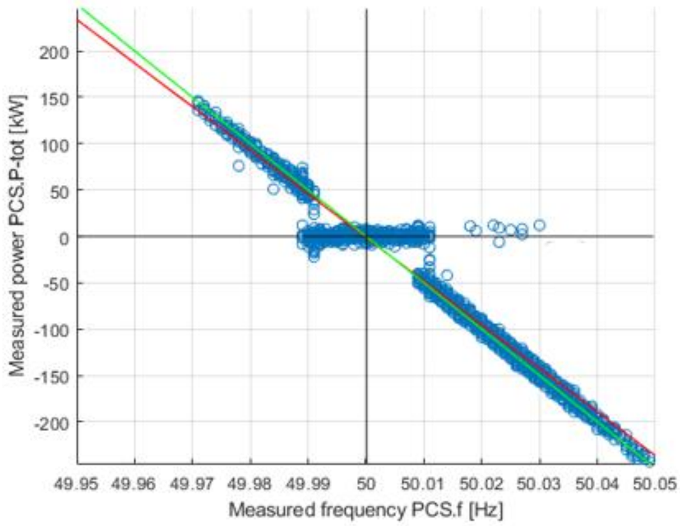


Figure 83: Check of the slope of FCR+ in the course of the field tests (Deadband = 10 mHz)

8.6 Analysis of regulatory framework

In this chapter, the implementation of the fast control reserve concepts is further evaluated with regard to regulatory aspects. The current regulatory framework, which can be considered as a basis for a future implementation, is described in subsection 8.6.1 and shows the results of a qualitative fit-gap analysis of the relevant regulatory framework. Within this frame, the fit-gap analysis mainly focuses on the necessary regulatory amendments, in order to ensure procurement of FCR+/EFR via reserve markets or to enable the trading of inertia certificates. Formal amendment processes of EU Network Codes/Guidelines and general consequences for a future implementation of fast control reserves are described in subsection 8.6.2.5.

8.6.1 Description of the relevant regulatory framework

The relevant regulatory framework within this work package can be categorized in different layers:

- EU law, which is directly applicable in each EU member state (network codes and guidelines):
    - Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation (GL SO)
    - Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing (GL EB)
    - Commission Regulation (EU) 2016/631 establishing a establishing a network code on requirements for grid connection of generators (NC RfG)

    - Commission Regulation (EU) 2016/1388 establishing a Network Code on Demand Connection (NC DCC)
- Methodologies, terms of conditions and non-exhaustive requirements, which have to be specified either on regional or national level and approved by the relevant national regulatory authorities (NRA)
- Other requirements or rules, which are part of national grid codes, prequalification rules or specific agreements between synchronous area TSOs:
    - The Synchronous Area Framework Agreement (SAFA) of the Continental Europe Synchronous Area is an updated collection of principles and rules for system operation. It replaces the former Operational Handbook (OH) of ENTSO-E and also references to relevant methodologies and terms of conditions, which are based on GL SO (Policy LFC&R as Annex of the SAFA)
    - National Grid Codes and requirements for prequalification

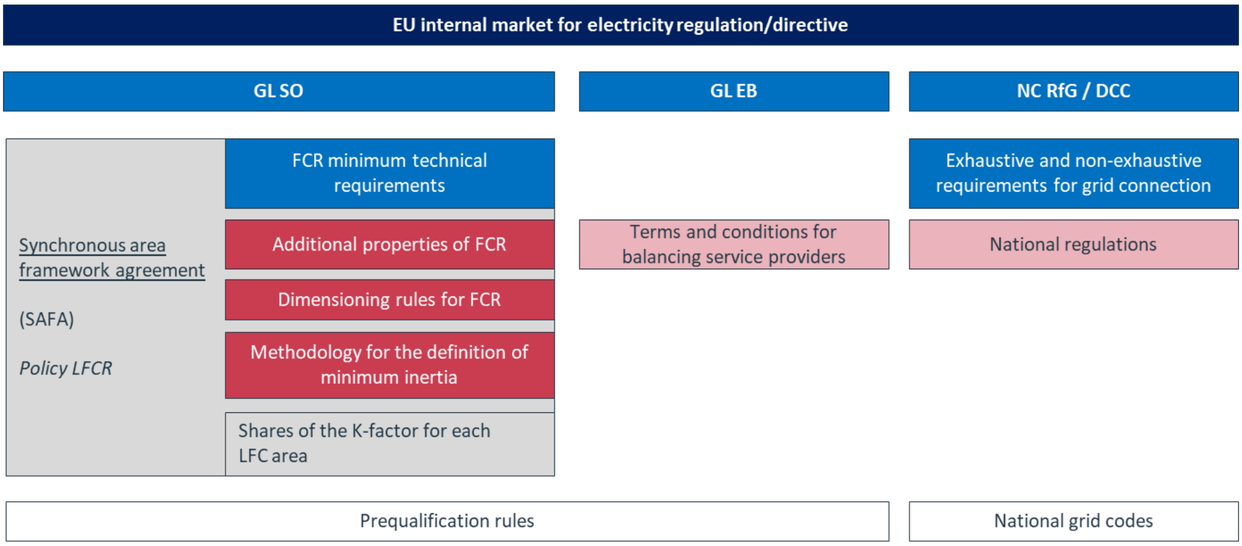


Figure 84: Description of the relevant regulatory framework

8.6.2 Fit Gap analysis

As part of the project, a fit gap analysis was carried out to determine the extent to which the outlined functionalities can be linked to the existing regulatory framework. The fit gap analysis furthermore aims to highlight required amendments in order to introduce the functionalities as market products, via certificates or mandatory grid connection rules.

8.6.2.1 Procurement of EFR/FCR+ via markets

Currently, there is almost no direct consideration of the fast control reserve concepts EFR or FCR+ on EU-level as potential fast reserve market products for the CE power system. The fit gap analysis shows that the regulatory framework would have to be adapted for the introduction of EFR/FCR+, as not all the necessary framework conditions are yet fully in place.

The fit gap analysis has identified the following relevant framework parts, which need to be amended, re-approved or updated:

- Amendment needed
    - FCR minimum technical requirements [GL SO Art. 154 (1) + Annex V]
    - Additional properties of FCR [GL SO Art. 154 (2)]
    - Dimensioning rules for FCR [GL SO Art. 153]
    - If necessary, terms and conditions for balancing service providers [GL EB Art. 18]
- Re-approval by NRAs
    - Additional properties of FCR [GL SO Art. 154 (2)]
- Re-design or update needed
    - SAFA (Policy LFC&R)
    - Prequalification rules

8.6.2.2 Inertia certificate trading (ICT):

The market for ICT could be organized similarly to existing certificate markets like guarantees of origin (GOs) or EU Emissions Trading System (EU ETS).

In this case a regulatory framework would need to cover at least the following aspects of an ICT process:

- Definition for the inertia certificates
- Calculation of provided SI based on measured feed-in data from DSOs / TSOs
- Allocation of inertia certificates based on the calculated SI
- Storage of inertia certificates
- Trading of inertia certificates between market participants
- Calculation of mandatory amount of inertia certificates per power plant based on feed-in data from DSOs / TSOs
- Verification of mandatory inertia certificate inventory per power plant

The fit gap analysis has identified the following relevant framework parts, which need to be amended, re-approved or updated:

- New definitions for technical requirements and dimensioning [GL SO]
- Methodology for the establishment of minimum amount of inertia certificates
- New definition for the inertia certificates market [GL EB]
- New definition for inertia certificates in national regulations [ElWOG]

8.6.2.3 Grid connection rules

Currently, potential approaches of the fast control reserve concepts EFR, FAPI and SI can be found on EU-level as grid connection rules for the CE power system. The fit gap analysis shows that the existing regulatory framework for grid connection requirements could be applied and if necessary extended, in order to cover the desired functionalities as connection requirements.

The fit gap analysis has identified the following relevant framework parts, which could serve as a basis:

- EFR - LFSM-O/U in NC RfG:
  According to NC RfG Art. 13.2 all new power generating modules shall be capable of automatically reducing their active power provision in case of overfrequencies. Furthermore, according to NC RfG Art. 15.2.c, new type C and type D power generating modules shall be also capable of increasing their active power provision in case of underfrequencies. The respective frequency thresholds and droop settings have to be specified by the relevant TSO in line with the limitations set out in NC RfG. In case of the CE power system the recommended values are 50,2 Hz for LFSM-O and 49,8 Hz for LFSM-U.

- SI/(FAPI) - NC RfG:
  According to NC RfG Art. 21.2.a the relevant TSO shall have the right to specify that type C and type D power park modules must be capable of providing synthetic inertia during very fast frequency deviations.

- EFR/SI/FAPI - NC DCC:
  According to NC DCC Art. 30.1 the relevant TSO may agree with a demand facility owner on a contract for the delivery of a very fast active power control.

Since the amendment of the connection network codes is a complex process, the services may initially be introduced at national level. However, as the frequency is linked within a SA, coordination between the TSOs is required in order to receive a desired behaviour. Therefore, a system-wide solution is generally favoured.

8.6.2.4 Formal amendment processes of EU Network Codes and Guidelines

In order to introduce some of the advanced functionalities proposed in this research project on a European level the relevant regulatory framework (i.e. network codes and guidelines) requires certain amendments. Along with the current regulation on the internal market for electricity EU/2019/943 as part of the clean energy package (CEP) a new amendment process for the existing network codes and guidelines was introduced.

8.6.2.4.1 Amendments of network codes (Art. 60 EU/2019/943)

Network codes are considered as "delegated acts" according to 59(2). Those implementing acts shall be adopted in accordance with the examination procedure referred to in Article 60:
All stakeholders may propose draft amendments to ACER. ACER shall consult all stakeholders on their proposals and self-developed proposals. Afterwards ACER makes reasoned proposals to the European Commission (EC), explaining the consistency with the regulation's objectives in providing final customers with safe and secure energy (system needs). The EC is empowered to amend the network codes in a formal process (comitology).

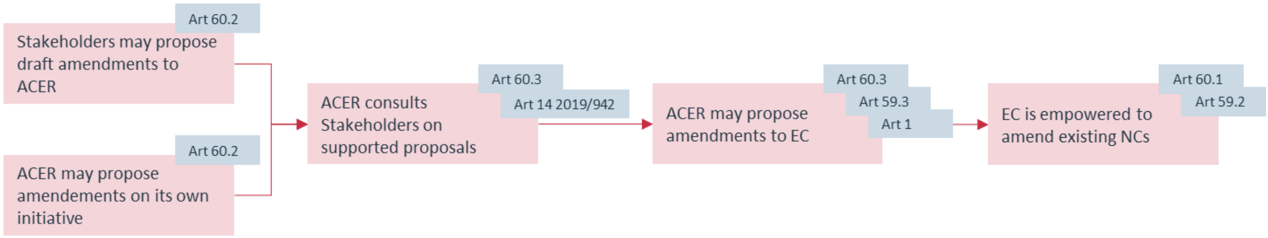


Figure 85: Amendment process of network codes

8.6.2.4.2 Amendments of guidelines (Art. 61 EU/2019/943)

<u>Guidelines are considered as “implementing acts”</u> according to 59(1). Those implementing acts shall be adopted in accordance with the advisory committee procedure (simplified comitology). The advisory committee consists of members from all EU member states. The EC is empowered to adopt guidelines in accordance with the regular committee procedure (advisory) according to Article 4 EU/182/2011. In the process it shall explicitly consult ACER, ENTSO-E, EU-DSO and if necessary relevant Stakeholders.

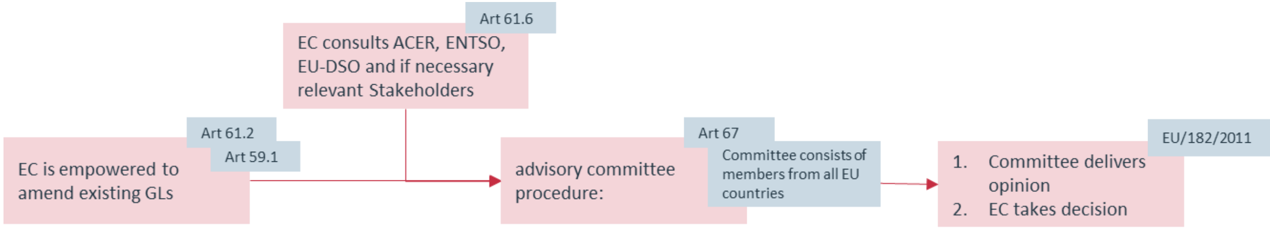


Figure 86: Amendment process of guidelines

8.6.2.5 Consequences for the implementation of new system services

Due to the formal process described above necessary amendments of the relevant regulatory framework would take several years until they enter into force on a national level. In order to meet the future system needs it is therefore required to start the necessary amendment initiatives on a European level early enough.

8.7 Conclusions and outlook

In order to ensure the desired system behaviour in the analysed scenarios, the development of an implementation roadmap for the CE power system is recommended. The implementation roadmap shall respect the results based on the common studies according to Art. 39 of the GL SO. This article requests all TSOs of a SA to conduct a common study every two years to identify whether a minimum required inertia needs to be established. If necessary all TSOs shall jointly develop a methodology for the definition of minimum inertia required to maintain operational security and to prevent violation of stability limits. That methodology shall respect the principles of efficiency and proportionality.

Taking into account the abovementioned principles of efficiency and proportionality, there is a need to consider a balance between the system needs, the capability of different technologies, the expectations from market participants and social welfare. Under this framework, national or regional pilot projects, including TSOs, market participants, manufacturers and regulators, could serve as a promising basis to demonstrate the cost-efficiency and effectiveness of different fast control reserve concepts. Additionally, the outcomes from such pilot projects (including this R&I project) could be also used for the development of future regulatory frameworks in the CE power system.

The exemplary implementation roadmap shown in Figure 87 can be considered as a potential starting basis for the CE power system.

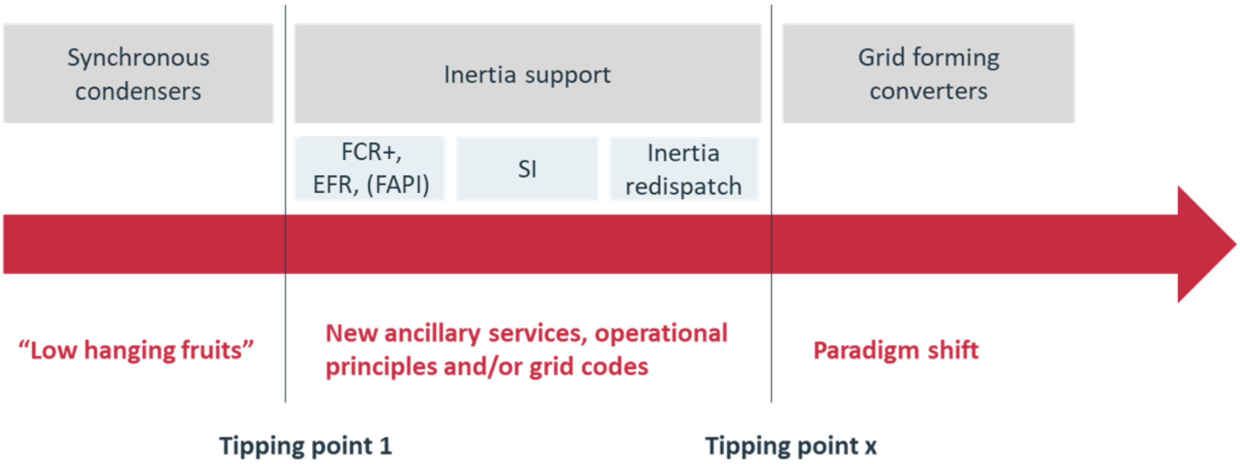


Figure 87: Exemplary implementation roadmap

As can be seen, the different proposed countermeasures can be categorized in different groups:

- <u>Countermeasures, which can be quickly implemented ("low hanging fruits")</u>
  The rapid change of power systems and concerns over the loss of inertia have stimulated new interest in synchronous condensers (SC). SC can mimic the operation of large conventional power plants by providing an alternative source of spinning inertia to stabilize the grid. A major advantage of SCs 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).

- <u>New ancillary services, operational principles and/or grid codes</u>
  FCR+, EFR (asymmetric) or inertia certificates basically have the highest suitability as future market products as there are several synergies with already existing balancing markets. An additional advantage of such future market products is that they could be

also provided by existing RPU/TE. Furthermore, potential approaches of the fast control reserve concepts EFR, FAPI and SI can be found on EU-level as grid connection rules for the CE power system and used as potential starting points. However, in order to introduce new market products or harmonized grid code requirements it is required to start the necessary amendment initiatives on a European level early enough.

- Paradigm shift (grid forming)
  Most inverter controllers today are grid-following and built on the assumption that system voltage and frequency are regulated by inertial sources. Such control approaches do not inherently provide an inertial response to the system and could be seen as the “root-cause” for potential frequency instabilities. This limitation has accelerated in-depth investigations into grid-forming control methods for new power electronic inverters, which provide functionalities that are traditionally provided by synchronous machinery. The practical implementation of grid-forming capability is currently under development and requires extensive preliminary studies in cooperation with experts and manufacturers, in order to establish harmonized specifications for the whole power system.

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10 List of Abbreviations

ABS4TSO	Advanced Balancing Services for Transmission System Operators
AIT	Austrian Institute of Technology
APG	Austrian Power Grid
BESS	Battery Energy Storage Systems
BM	Balancing Mechanism
BOA	Bid-offer Acceptance
CE	Continetal European
CEP	Clean Energy Package
C-HIL	Controller Hardware-to-the-loop
CLPU	Cold Load Pickup
CNC	Connection Network Codes
DAQ	Data Acquisition
DC	Dynamic Containment
DC-HF	DC high frequency
DC-LF	DC low frequency
DFD	Deterministic frequency deviation
DM	Dynamic Moderation
DR	Dynamic Regulation
EC	European Comission
EDisOn	Electricity Dispatch Optimisation
EFR	Enhanced Frequency Response
ElWOG	Elektrizitätswirtschafts- und Organisationsgesetz
ENTSO-E	European Network of Transmission System Operators for Electricity
ESO	Electricity System Operator
EU ETS	EU Emissions Trading System
EUCO 2030	
EUT	Equipment under test
FAPI	Fast Active Power Injection
FCR+	Frequency Containment Reserve+
FFG	Austrian Research Promotion Agenty
FFR	Fast Frequency Response
FR	Fast Reserve
GA	Global Ambition
GHG	Green House Gas
GL EB	Giudeline on Electrcity Balancing
GL SO	Policy LFC & R as Annex of the SAFA
GO	Guarentees of Origin
HIL	Hardware-to-the-Loop
HVAC	Heat, Ventilation and Air Conditioning
H-Value	Inertia Values
Hz	Hertz
KPI	Key Performance Indicator
kWh	Kilowatt hour
LVRT	Low Voltage Ride Through
MVA	Mega Volt ampere
MW	Megawatt

NC DCC	Network Code on Demand Connection
NC RfG	Network Code on Requirements for Grid Connection of Generators
NECP	National Energy and Climate Plans
NT	National Trends
NTC	Net Transfer Capacity
OH	Operational Handbook
PSR	Power System Restoration
PSS	Power System Stabilizer
RfG	Requirements frp Generators
RGCE	Regional Group Continental Europe
RoCoF	Rate of Change of Frequency
RPU	Reserve Providing Units
RTS	real-time Simulator
SA	Synchronous Area
SA	Synchronous Area
SAFA	Synchronous Area Framework Agreement
SC	Synchronous Condensers
SI	Synthetic Inertia
SoC	State of Charge
TCL	Thermoststic Controlled Loads
TE	Technical Entities
TSO	Transmission System Operator
VT	Voltage Transformer
WP	Work Package

11 Annex

11.1 Market monitoring / product analysis:

TSO	Synchronous area	Abbreviation	Full product name	Basic description and motivation for the introduction	Status
National Grid	GB *200-300 GWs Reference incident ≈ 1 GW*	DC	Dynamic Containment	It is planned to release DC as the first of new end-state products, in order to meet the most immediate need for faster-acting frequency response; The product is designed to operate post-fault, i.e. for deployment after a significant frequency deviation;	Planned 2020
NORDIC TSOs	NORDIC *200-300 GWs Reference incident ≈ 1,45 GW*	FFR	Fast Frequency Response	FFR as a new static product is deemed the most promising mitigation measure for low inertia situations since several technologies can provide fast active power response estimated at low socio-economic costs; According to the feasibility study, FFR is a more cost-efficient measure for handling low inertia challenges compared with reducing the size of reference incident or procuring more existing reserves (FCR-D); It acts as a complement to FCR-D. FFR does not reduce the need of FCR-D, thus, does not replace FCR-D;	In operation May 2020
TERNA	Continental European synchronous area	FR	Servizio di Regolazione Ultra-Rapida or Fast Reserve	The main idea is to provide a continuous and automatic response to the frequency error in the grid (in terms of deviation from the nominal value of 50 Hz). The response is provided within 1 second of the event that caused the activation of the service or in response to a change in the set-point sent by Terna and with a start-up time not exceeding 300 milliseconds.[iii] Terna highlighted the need to define a new ancillary service to manage the consequences of the expected decrease in inertia (due to the reduction of production plants equipped with rotating machines. In particular, those moved by masses of steam that come out of the boilers - and to the simultaneous increase in production plants powered by renewable sources equipped with static elements such as inverters). More in detail, the progressive reduction of systemic inertia determines an increment of frequency variations that must be contained in extremely rapid response times, not always compatible with the current contribution of primary frequency regulation.[iii]	Planned 2023[ii]

	National Grid	**NORDIC TSOs**	**TERNA**
	Dynamic Containment (DC)	***Fast Frequency Response (FFR)***	***Fast Reserve (FR)***
Technical requirements			
Input signal	Frequency	Frequency	Frequency
Control scheme	Frequency proportional (droop)	Static (frequency threshold)	Frequency proportional (droop)
Product range	Symmetric *(in the future it is planned to move to an asymmetric product range)*	Asymmetric (only under-frequency) *(currently not planned to implement over-frequency response)*	Symmetric
Minimum initial delay (MID)	0,25 s ≤ t_{MID} ≤ 0,5 s	0,7 s (activation level @49,5 Hz) 1,0 s (activation level @49,6 Hz) 1,3 s (activation level @49,7 Hz)	<300ms delay
Full activation time (FAT)	0,5 s ≤ t_{FAT} ≤ 1,0 s		<1s Full activation time
Minimum activation time	15 min (full activation)	*Long support duration FFR* (support duration ≥ 30 s) *Short support duration FFR* (support duration ≥ 5 s) *The FFR providing entity must be ready for a new FFR activation cycle within 15 minutes after the activation instant;* *The FFR providing entity may stay active as long as the frequency is below 49,8 Hz and start the deactivation sequence when the frequency exceeds 49,8 Hz;*	>30s "Fast reserve Units" must have enough capacity such as to permanently allow the provision of the offered power, symmetric, for at least 15 consecutive minutes every 2 hours. Therefore, for storage systems, the requirement can be expressed in a minimum energy / power ratio of at least 0.5
Deactivation time	--	*Long support duration FFR* *No limitation in the rate of deactivation (stepwise deactivation is allowed)* *Short support duration FFR* *Rate of deactivation is limited to maximum 20 % of the prequalified FFR capacity per second*	perform a linear de-ramp until it is cancelled in 5 minutes
Maximum acceptable overshoot	--	35 % of the prequalified FFR capacity	5 % of the offered power
Full activation frequency deviation	± 0,5 Hz	--	± 0,2Hz
Frequency response deadband	± 0,2 Hz *Small linear delivery is required between ± 0,015 Hz and ± 0,2 Hz, to a maximum of 5 % of the prequalified DC capacity at ± 0,2 Hz*	49,5 Hz / 49,6 Hz / 49,7 Hz	Adjustable [0±0,5Hz] (usually ± 0,2 Hz)
Frequency measurement requirements			
Location	Local f-measurement Optional: Centralized f-measurement	Local f-measurement Optional: Centralized f-measurement	Local f-measurement
Resolution	50 ms	100 ms	50ms
Accuracy	≤ 10 mHz	≤ 10 mHz	≤ 5mHz

Prequalification and monitoring			
Prequalification concept	Each individual asset within any aggregated unit must pass prequalification and testing Provider has to perform standard tests: • Step response test • Standard frequency profiles • Duration test • Connection to the grid test	Provider has to perform standard tests: • Step response test • Ramp test • Standard frequency profiles 5 years validity (simplified reassessment using system natural frequency variations as test signal can be performed)	The geographic perimeters of the aggregated units cannot exceed the bidding zones. At the time of first qualification for the service, specific real tests are required to confirm the technical characteristics and compliance of the system: • Detection of the capability the offered power. • For both directions verification of the activation times (<1s) • Activation tests • Verification of the management function of the state of energy capacity, if implemented.
Monitoring concept	In order to check, if a unit is available each provider has to send real-time data (resolution ≤ 1 s) • active power signals for each asset within a unit Performance monitoring ex-post, when requested by the TSO (spot checks, no real-time data transfer) Performance monitoring data (has to be stored for at least 14 days) • Grid frequency • Baseline • Active power (accuracy ≤ 1 %)	In order to check, if a unit is available each provider has to send real-time data (resolution ≤ 60 s) • Maintained FFR capacity [MW] • (the maintained FFR capacity includes both contracted and non-contracted capacity). Performance monitoring ex-post, when requested by the TSO (spot checks, no real-time data transfer); Trust in the reliability and proper activation once the prequalification tests were successful Performance monitoring data (has to be stored for at least 14 days) • Grid frequency • Maintained FFR capacity • Instantaneous active power (accuracy ≤ 0,5 %) • Controller set-point • Control mode	Terna verifies that the Fast Reserve Unit is actually available to provide the ultra-fast regulation service in each hour of availability. Phasor measurement unit (PMU) device interfaced with Terna's systems
Baseline concept	Baseline is needed – usually reflects schedule (generally schedules are unchangeable at least one hour before delivery) For large plants more sophisticated mechanisms for the provision of baseline are needed	No Baseline used	The baseline reflects schedule
Penalty system	Penalty system is quite challenging to establish (it should not be too strict to keep providers in the market)	No formal procedure yet (no penalties) A temporary ban from participation could be possible (until problems are fixed)	If the Fast Reserve Unit is not available to provide the ultra-fast regulation, Terna applies penalties for each hour, related to the fixed

	Paying for availability will be reduced, if quality is not met A temporary ban from participation could be also possible (until problems are fixed)		hourly fee (calculated as the ratio between the annual fixed fee and 1000 hours). In particular: • in the case that, during the hour, the average power available is between 80% and 95% of the offered power, the penalty is equal to the product between the difference between the offered power and the average power actually made available and the 120% of the fixed hourly fee; • In the case that, in one hour, the average available power is less than 80% of the offered power, the penalty is equal to the product between the offered power and 120% of the fixed hourly fee.
Need for NRA approval	only terms & conditions	only terms & conditions	only terms & conditions
Size and dimensioning approach			
Description	Dynamic based approach	Dynamic based approach (hourly inertia and necessary amount of FFR)	Static dimensioning of the ancillary service
Inputs	Forecasts (reference incident, inertia, RES-share, load)	Market model simulations and forecasts (reference incident, inertia, RES-share, load, weather conditions,..)	Market model scenarios of the “Piano Nazionale Integrato Energia e Clima” (PNIEC) (grid inertia and RES-share) The goal is to maintain the actual dynamic characteristics of the grid.
Additional information	Volumes of DC are highly dependent on reference incident; Operator may also limit reference incident (e.g. limit interconnector exchanges)	Need of FFR is mainly concentrated around the summer and depends heavily on hydrological situation The sharing key for FFR in the NORDIC synchronous area is based upon the FCR-N/D with a correction factor for the contribution to the inertia and the size of the reference incident of the country	The new service is not a substitute for primary regulation but a coordinated service with it With reference to each area, each corporate group cannot be assignee for more than 40% of the requirements of the same area, except in the case in which the offers presented by the other participants are not sufficient to cover the needed capacity.
Market aspects			
Tendered volumes Procurement	~ 250 MW initially (up to 1 GW) Tendered volumes will grow with the available market and TSO system readiness Procurement is symmetrically (under-/over-frequency);	~ 250 - 300 MW Procurement via national markets (hourly basis)	North and Center-North→100MW Center-South, South and Sicily →100MW Sardinia→30MW

	in the future it is planned to procure under-/over-frequency product separately		
Minimum bid size	1 MW Aggregation is possible (if same location/site) *(in the future the minimum bid size might be reduced)*	1 MW Aggregation is possible	(Aggregation is possible) 5MW
Maximum bid size	--	10 MW	25MW
Maximum size per unit	50 MW	50 MW	25MW
Remuneration system	Providers are paid for availability only, minus unavailability and a service performance measure (SPM) <u>Other elements that may be included in the SPM:</u> • Accuracy and reliability of data provision • Performance against baseline	<u>Finland, Sweden:</u> • Marginal pricing • Power only (no energy/activation compensation) <u>Denmark:</u> • The energy activation, if any, will be settled at the imbalance price <u>Norway:</u> • Marginal pricing • Power + activation	- pay-as-bid power price : <80k€/MW/year →Merit order. -Energy price: The Fast Reserve Unit receives from Terna, if positive, and pays Terna, if negative, an hourly fee. The fee is equal to the product of the valuation price of the sales offers on the day ahead spot market in the same reference period and in the same area market in which the Fast Reserve Unit is located. The energy exchanged for the supply of the service itself as well as for the restoration of the energy capacity of the Fast Reserve Unit. These power flows cannot create balancing costs.
Organizational aspects	Weekly (planned daily)	<u>Finland:</u> Daily <u>Sweden:</u> Seasonal market (D-1 procurement in the future) <u>Denmark:</u> monthly capacity auctions (planned daily/hourly) <u>Norway:</u> seasonal market	5-years-contract. The assignees accept to make the Power offered available for 1000 hours per year. In this regard, Terna publishes an initial estimate of the hours of availability for the following year by 31 October of each year. Subsequently, seven days in advance, Terna communicates a more accurate estimate of the hours in which to guarantee availability. Two days in advance, Terna communicates the precise hours in which to guarantee availability.
Remarks	DC cannot be stacked with existing response and reserve products, but it is intended to allow stacking with new response and reserve products introduced in the future		
Need for NRA approval	only terms & conditions	only terms & conditions	only terms & conditions
Miscellaneous			
Technologies used	Mainly batteries (typically 20 MW) and HVDCs	Mainly batteries and loads Hydro power plants are usually not fast enough	Storage systems, in particular in combination with relevant production units.
Number of activations	--	Trial phase (2017-2018):	1000h/year.(availability)

		The frequency crossed the activation threshold values for FFR in 2017 and 2018 very rarely Activation times in 2017 and 2018 49,7 Hz --> 9 activations 49,6 Hz--> 3 activations 49,5 Hz --> 0 activations	
Prospects for the future	Static products will be replaced by pure frequency proportional products Dynamic containment will be followed by dynamic moderation and dynamic regulation	work towards a common Nordic FFR market	

11.2 Detailed market analysis

EFR	Scenario 1: tender market analogous to existing control reserve products tender with symmetrical products			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

EFR	Scenario 2: market alternativ Tender with asymmetric products (delivery | purchase)			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

FCR+	Scenario 1: tender market analogous to existing control reserve products Procurement within the framework of the existing FCR-tender.			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
Price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

SI	Scenario 1: tender market analogous to existing control reserve products Tender with symmetric products			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
Price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

	Scenario 2: market alternative			
SI	**Certificate trading**			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

	Scenario 1: tender market analogous to existing control reserve products			
FAPI	**Tender with symmetric products**			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

	Scenario 2: market alternative			
FAPI	**Tender with asymmetric products (delivery | purchase)**			
market criteria				
market integration	market area	synergy	product range	
market liquidity	level playing field	incentive	technology neutral	
market entry	product requirement	product complexity	implementation effort	automation
price evaluation	costs	profits		
market rules	trading procedure	trading products	price formation	

market integration: market area	
requirement:	**synergies with existing markets**
premises:	**consistent goals, product requirements, capacities**
EFR – scenario 1 EFR – scenario 2	(-) higher shares in control areas (assumption: product similar to LFSM-O/U for large frequency deviations)
FCR+ – scenario 1	(+) market area analogous to existing FCR.
SI – scenario 1	(-) higher shares in control areas necessary (ensure equal distribution of the product due to the increased dynamic)
SI – scenario 2	(-) limited contingent of freely tradable certificates in the synchronous area (ensuring an equal distribution of inertia)
FAPI – scenario 1 FAPI – scenario 2	(-) higher share in individual control areas necessary (-) difficulties with uniform product design through TSOs coordination (frequency trigger events)

market integration: synergy	
requirement:	**synergies with existing markets**
premises:	**use of existing processes and platforms**
EFR – scenario 1	(+) established markets could be used, but own tender periods, minimum sizes, etc. would be necessary.
EFR – scenario 2	(~) due to other market participants and plant operators are to be addressed here, hardly any synergies with existing reserve markets would be possible.
FCR+ – scenario 1	(+) very well applicably by using the existing FCR market. Same tender period, faster activation time
SI – scenario 1	(-) due to the very high dynamics and technical differences to existing control reserve products (e.g. FCR), new platforms are most likely required
SI – scenario 2	(-) new certificate markets required
FAPI – scenario 1 FAPI – scenario 2	(-) due to the very high dynamics and technical differences to existing control reserve products (e.g. FCR), new platforms are most likely required

market integration: product range	
requirement:	**smart addition to existing product range**
premises:	**DayAhead, IntraDay, control reserve market, congestion management**
EFR – scenario 1 EFR – scenario 2	(~) less but possible applicably in existing product range (new product, prequalification and monitoring, stand-alone)
FCR+ – scenario 1	(+) highly applicably in existing product range.
SI – scenario 1	(~) less but possible applicably in existing product range (new product, prequalification and monitoring, stand-alone)
SI – scenario 2	(~) could be applicably for existing power plants with inertia (add-on), but still a new product, new prequalification and monitoring

FAPI – scenario 1 FAPI – scenario 2	(~) less but possible applicably in existing product range (new product, prequalification and monitoring, stand-alone)
market liquidity: level playing field	
requirement:	**uniform requirements and maket design**
premises:	**product requirements according table**
EFR – scenario 1 EFR – scenario 2 FCR+ – scenario 1	(+) uniform requirements and market design highly applicably
SI – scenario 1 SI – scenario 2 FAPI – scenario 1 FAPI – scenario 2	(+) uniform requirements and market design possible applicably
market liquidity: incentive	
requirement:	**revenue potential must cover costs and offer new potentials**
premises:	**for new and existing plants**
EFR – scenario 1 EFR – scenario 2	(+) Incentive for entry of assets that cannot be applied in other flexibility markets.
FCR+ – scenario 1	(+) Incentive for existing FCR providers to offer certain plants on the FCR+ market. (+) Incentive also exists in principle for plants which do not currently participate in existing control reserve markets.
SI – scenario 1	(+) Incentive for market entry of plants that cannot be used in other flexibility markets (e.g. flywheels).
SI – scenario 2	(-) through a long-term certification, market entry is worthwhile for many existing and new plants.
FAPI – scenario 1	(+) simple market entry for aggregators as wind power due to low technical requirements. (~) Lower product value / revenue opportunities offers less incentive for operators of highly flexible plants to enter the market
FAPI – scenario 2	(+) Even simpler technical requirements due to separation of supply and purchase, improve the market entry for aggregators (wind power, controllable loads such as heat pumps)
market liquidity: technology neutral	
requirement:	**applicable as many different technologies as possible**
premises:	**product requirements**
EFR – scenario 1	(+) basically suitable for many plant types
EFR – scenario 2	(+) is suitable for many plant types (also consumers)
FCR+ – scenario 1	(+) is suitable for many plant types (part of existing FCR-plants)
SI – scenario 1	(~) is basically suitable for fewer plant types
SI – scenario 2	(+) very suitable in case of implementation of an inertia certificate market
FAPI – scenario 1	(~) is suitable for fewer plant types (more specific to wind power)
FAPI – scenario 2	(+) is suitable for many plant types (also consumers)
market entry: product requirement	
requirement:	**prequalification and quality of delivery should be applicable of different technologies**
premises:	**technology requirements**
EFR – scenario 1	(+) prequalification and quality of delivery is possible with different technologies (+) market entry similar to FCR (+) due to infrequent activation, continuous monitoring may not be necessary - subsequent recording must be possible.
EFR – scenario 2	(+) prequalification and quality of delivery is possible with different technologies (+) asymmetric design allows more participants (e.g. consumption units) (+) market entry similar to FCR. (+) Due to infrequent activation, continuous monitoring may not be necessary - subsequent recording must be possible.
FCR+ – scenario 1	(+) prequalification and quality of delivery is possible with different technologies (+) market entry similar to FCR. (-) continuous monitoring only economical for certain plant sizes.
SI – scenario 1	(+) all converters could contribute, also consumers, HVDC (-) no existing prequalification procedure of SI applicable. (~) regular proof of correct function would be required in any case, self-monitoring. (-) precise frequency measurement and detailed monitoring are necessary. Economical for a certain plant size.
SI – scenario 2	(+) certificate from all inertia-providing systems (also consumers, synchronous systems, HVDC, etc.). (~) conformity ensured by regular certificate acquisition. (-) high administrative effort to monitor the certificates and certificate allocation.
FAPI – scenario 1	(+) prequalification and quality of delivery is possible with different technologies (~) Due to static triggers, rather simple prequalification procedure (+) Due to infrequent activation, continuous monitoring may not be necessary - subsequent recording must be possible.

FAPI – scenario 2	(+) prequalification and quality of delivery is possible with different technologies (+) asymmetric design allows more participants (e.g. consumption units) (~) Due to static triggers, rather simple prequalification procedure (+) Due to infrequent activation, continuous monitoring may not be necessary - subsequent recording must be possible.
market entry: product complexity	
requirement:	**product definition as simple as possible**
premises:	**product differentiation: energy direction, size offer, tender timing, dynamic sizing**
EFR – scenario 1 EFR – scenario 2	(+) robust “emergency product” thus long-term tender periods (+) Form TSO’s point of view, clear technical requirements and robust functionality
FCR+ – scenario 1	(+) similar tender periods than FCR
SI – scenario 1	(~) if necessary, shorter tender periods
SI – scenario 2	(+) simple handling due to certificate market
FAPI – scenario 1 FAPI – scenario 2	(~) if necessary, shorter tender periods
market entry: implementation effort	
requirement:	**participation with minimal process effort**
premises:	**market entry economical even with low transaction volume**
EFR – scenario 1 EFR – scenario 2 FCR+ – scenario 1	(+) using the existing FCR infrastructure
SI – scenario 1 SI – scenario 2	(~) new processes for marketing and monitoring required
FAPI – scenario 1 FAPI – scenario 2	(~) new processes for marketing and monitoring required (-) coordination of TSOs regarding staggering
market entry: automation	
requirement:	**interface for fully automated trading**
premises:	**for providers with high transaction volume**
EFR – scenario 1 EFR – scenario 2	(~) certain adaptations compared to FCR necessary
FCR+ – scenario 1	(+) use of FCR infrastructure possible
SI – scenario 1 SI – scenario 2 FAPI – scenario 1 FAPI – scenario 2	(~) new processes for marketing and monitoring required
price evaluation: costs	
requirement:	**price evaluation includes all cost components**
premises:	**cost components: investment costs, fixed cost, variable costs, opportunity costs, price risk**
EFR – scenario 1	(~) investment costs moderate (-) high opportunity costs relative to call-up duration
EFR – scenario 2	(~) Investment costs moderate, but lower than in scenario 1 (~) Opportunity costs relative to call-up duration high, but lower than in scenario 1
FCR+ – scenario 1	(~) Investment costs moderate (+) Opportunity costs do not or only slightly increase compared to FCR
SI – scenario 1	(-) Investment costs high - very complex function (~) Opportunity costs moderate, through less power will be reserved
SI – scenario 2	(-) investment costs high - very complex function (+) No investment costs for providers of rotating machines (~) Opportunity costs rather moderate, as less power need to be reserved
FAPI – scenario 1 FAPI – scenario 2	(+) easy and inexpensive implementation (+) Opportunity costs rather low, as no power need to be reserved
price evaluation: profits	
requirement:	**Revenue potential assessable in mid-term**
premises:	**Market entry and investments are made on the basis of revenue potential estimates**
EFR – scenario 1	(~+) slightly less competition lead to a slightly increased revenue potential compared to existing markets. (~) Possibility of aggregation could increase competition and thus reduce revenue potential from market participant perspective
EFR – scenario 2	(~) Asymmetric tender would allow more competition and thus lower revenue potential

	(~) Possibility of aggregation could increase competition and thus reduce revenue potential from market participant perspective
FCR+ – scenario 1	(+) slightly increased revenue potential, due to fewer market participants
SI – scenario 1	
SI – scenario 2	(~+) Revenue potential is especially based on the number of traded certificates --> slightly increased revenue potential compared to existing comparable markets (+) Additional revenue potential for conventional plants (with inertia)
FAPI – scenario 1	(~+) slightly less competition lead to a slightly increased revenue potential compared to existing markets. (~) Possibility of aggregation could increase competition and thus reduce revenue potential from market participant perspective
FAPI – scenario 2	(~) Asymmetric tender would allow more competition and thus lower revenue potential (~) Possibility of aggregation could increase competition and thus reduce revenue potential from market participant perspective
Market rules: trading procedure	
requirement:	**Decision between call auctions or continuous trading**
premises:	**Continuous trading only applicable with strong Intra-Day price movement und high transaction volume**
EFR – scenario 1	(+) Product fits into current market design. Defined by: symmetric, power price and auction (-) Due to rare activation, not applicable for continuous trading
EFR – scenario 2	(~) Asymmetric tender would allow more competition and thus lower revenue potential (~) Possibility of aggregation could increase competition and thus reduce revenue potential from market participant perspective
FCR+ – scenario 1	(+) Continuous Trading, identical to FCR
SI – scenario 1	(~) Difficult classification, as there is no measurable product at the market
SI – scenario 2	(+) Certificates are good applicable for continuous trading
FAPI – scenario 1	(+) Product fits into current market design. Defined by: symmetric, power price and auction (-) Due to rare activation, not applicable for continuous trading
FAPI – scenario 2	
Market rules: trading products	
requirement:	**Decision between call auctions or continuous trading**
premises:	**Continuous trading only applicable with strong Intra-Day price movement und high transaction volume**
EFR – scenario 1	(+) absolute power product (~) products definable by several options limited by symmetrical and longer-term tender
EFR – scenario 2	(+) absolute power product (~) products definable by several options limited by longer-term tender
FCR+ – scenario 1	(+) absolute power product (~) products definable by several options limited by symmetrical tender
SI – scenario 1	(-) more complex product definition
SI – scenario 2	(+) certificate trading
FAPI – scenario 1	(+) absolute power product (~) products definable by several options limited by symmetrical tender
FAPI – scenario 2	(+) absolute power product (~) products definable by several options
Market rules: price formation	
requirement:	**Decision between pay-as-bid or marginal pricing**
premises:	**Marginal pricing only makes sense in the case of a high supply surplus**
EFR – scenario 1	(~+) less participants, pay-as-bid applicable
EFR – scenario 2	(~+) less participants, pay-as-bid applicable
FCR+ – scenario 1	(+) high number of participants, pay-as-bid or marginal pricing applicable
SI – scenario 1	(~) few participants, pay-as-bid applicable
SI – scenario 2	(~+) pricing of inertia by certificate in pay-as-bid trading
FAPI – scenario 1	(~+) less participants, pay-as-bid applicable
FAPI – scenario 2	(+) high number of participants, pay-as-bid or marginal pricing applicables

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