



TwinEU digital twinning for fast frequency response

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List of Abbreviations and Acronyms

Acronym	Meaning
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
CEP	Clean Energy Package
DSA	Dynamic Security Assessment
DSO	Distribution System Operator
EMS	Energy Management System
ESM	Electricity Storage Module
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
LV	Low Voltage
MV	Medium Voltage
PPM	Power Park Module
RfG	Requirements for Generators
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SOGL	System Operation Guidelines
SPGM	Synchronous Power-Generating Module
TSO	Transmission System Operator
V2G	Vehicle-to-Grid

Executive Summary

The rapid evolution of power systems — driven by the increasing integration of inverter-based renewable energy sources, distributed generation, and the necessity for real-time security assessments — has redefined the operational challenges for grid operators across Europe. The TwinEU project addresses these challenges by developing advanced digital twin technologies that integrate both static and dynamic security assessment tools.

This deliverable D7.5 represents the technical report on the work done within the Task 7.7, which is a part of the Slovenian demonstration, showcases the proposal of implementation and simulations (testing) of new ancillary (system) service called Fast Frequency Response – FFR in the electric power system of Continental Europe.

Key outcomes and outputs include:

- Analysis of the purposes and objectives of the FFR service.
- Regulatory overview and analysis.
- Detailed concept proposal of FFR and its top-to-bottom characteristics., including:
 - Development of the concept of system operation criteria (TSO, NEMO) and technical criteria (balancing providers).
 - Definition of the FFR product and use case.
 - Development of the algorithm for service activation.
- Development of the use-cases, testing environment - simulations, and result analysis.
- Conclusions separating:
 - Key findings and
 - Proposal for further work.

The Slovenian demonstrators prove that the digital twin approach not only improves the precision of dynamic simulations but also prepares the system operators for a clear, simple, scalable and precise ancillary service which emerges due to the electric power system development in the era of green transition. This integrated methodology of the FFR paves the way for a more resilient and responsive power system, capable of handling the uncertainties and variabilities introduced by high renewable penetration such as volatility of the electric power system dynamics and stability.

1 Introduction

The electrical power system is facing challenges in recent years how to efficiently integrate large quantities of distributed renewable sources on one hand and new relatively large loads such as heat pumps and e-mobility on another. Gradual phase out of traditional fossil fuel power plants and large share of renewables is impacting the grid operation and requires new tools and approaches in the control centre. In these demonstrations we will present how developing and enabling such tools will allow continuous efficient, safe and reliable operation of the power system.

1.1 Overview of Slovenian power grid

The Slovenian power system integrates high-voltage transmission networks with medium and low voltage distribution systems. At the transmission level, the network operates primarily with 400, 220, and 110 kV lines, which facilitate long-distance power transport and interconnection with neighbouring European systems. The grid is managed by the combined transmission and distribution system operator ELES, which provides detailed models that simulate both steady-state conditions and dynamic events. [1]

The Slovenian power system is represented at the following figures [2]:

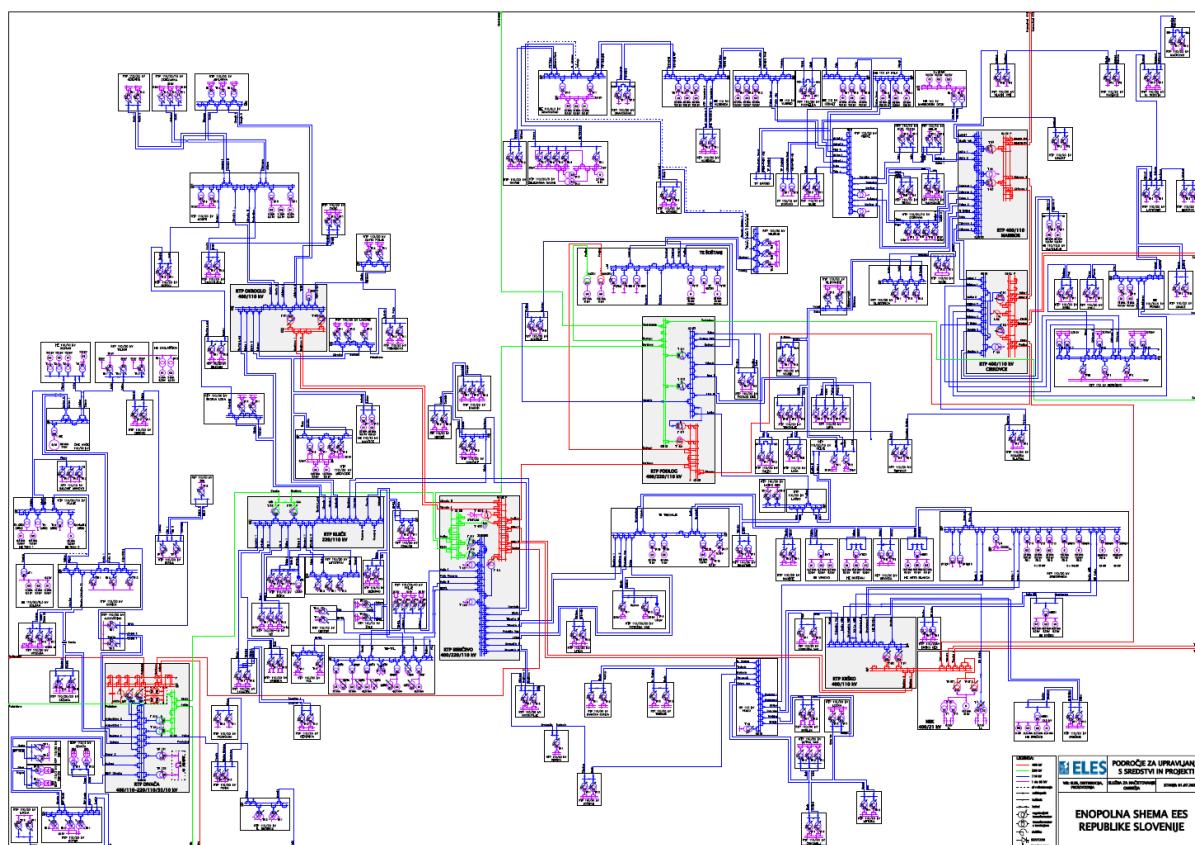


Figure 1-1 – Slovenian Electric-Power System (Single-line diagram of the 400, 220 and 110 kV level)
[2]

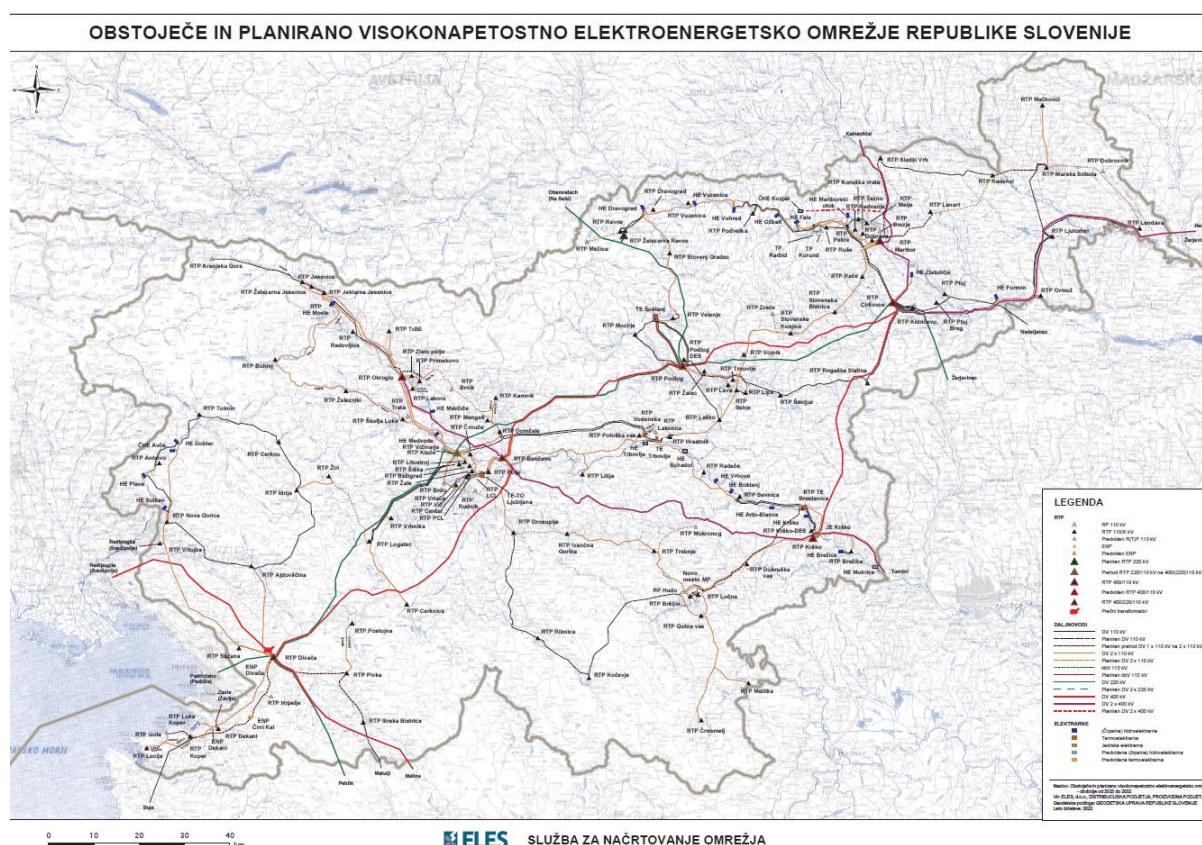


Figure 1-2 – Slovenian Electric-Power System (Geographic diagram of the 400, 220 and 110 kV level) [2]

Key aspects¹ of the Slovenian power system include:

- Interconnection and Border Dynamics:**
 Slovenia's transmission system is tightly interconnected with the Continental European (CE) network. This means that the system's dynamics are influenced not only by domestic power-system elements (e.g. generation and load) but also by those connected externally, outside national borders. Tie-lines and border nodes play a critical role in these interactions, serving as points for data and power exchange and consequently integration of external grid models.
- High Renewable Penetration:**
 In recent years, Slovenia has experienced significant growth in renewable energy installations, particularly in photovoltaic (PV) and wind power. These renewable sources contribute to a variable generation profile that challenges knowledge on stability properties of grids supplied by conventional generation. The fluctuating nature of renewables necessitates appropriate dynamic modelling techniques to capture the rapid transitions in generation and load.
- Diverse Load Profiles:**
 The grid serves a mix of industrial, commercial, and residential loads. These loads exhibit different voltage/frequency sensitivities and consequently individual dynamic responses.

¹ The aspects of the Slovenian power system and the Slovenian TwinEU demo are coordinated among all of the relevant tasks and deliverables. This section may purposely appear the same in those deliverables.

Industrial loads tend to be more stable and predictable, whereas residential loads can be highly stochastic and influenced by consumer behaviour and environmental factors.

- **Infrastructure Upgrades:**
Recent investments in the network modernization have focused on enhancing monitoring and control capabilities. The deployment of advanced SCADA/EMS systems has improved the real-time visibility of network conditions, while new technologies in digital metering and communication have facilitated the collection of high-resolution operational data.
- **Dynamic Model Fidelity:**
The dynamic models used by ELES incorporate detailed representations of generators, FACTS (Flexible AC Transmission System) devices, and network compensation systems. These models are critical for simulating transient events such as faults, sudden load changes, or generator outages. However, the accuracy of these models is continually challenged by the evolving grid conditions and the increasing integration of DERs.

Overall, the Slovenian power system represents a complex, dynamic environment where traditional analysis methods must be augmented by digital twin technologies and real-time data integration. The insights gained from this detailed overview form the basis for developing a new ancillary (system) service that can respond to the rapid changes in grid conditions.

1.2 The Slovenian demo

The Slovenian demo is serving as a live testbed to showcase the application of digital twin technology in dynamic security assessment tool (DSA) and creation of a proposal of a new ancillary service called Fast Frequency Response (FFR). Slovenia's power system, with its unique blend of high-voltage transmission lines and a rapidly evolving distribution network, presents an ideal environment for testing innovative grid management solutions. The demonstrator integrates detailed models of the Slovenian transmission system—with its interconnections to neighbouring European networks—with advanced representations of distributed generation and voltage-sensitive loads in the distribution system [3].

The choice of Slovenia is driven by several factors:

- **High Renewable Penetration:** The Slovenian grid has seen a significant rise in renewable installations—particularly (roof-top) photovoltaic—which introduce variability and require more agile stability assessment tools.
- **Interconnected Network:** Slovenia's grid forms an integral part of the Continental European (CE) interconnection. The dynamic interactions between the domestic grid and neighbouring systems provide a realistic setting to evaluate the influence of disturbances on local stability.
- **Operational Complexity:** With an increasing share of decentralized generation and dynamic load profiles, the Slovenian grid exhibits complex behaviour that traditional static models cannot fully capture. This calls for a comprehensive digital twin approach that models both steady-state conditions and dynamic responses to disturbances in real time.
- **Pilot Environment:** The demonstrator is deployed within the infrastructure of ELES, the national system operator, where real-time data are collected via SCADA/EMS systems. This live environment facilitates the testing and validation of dynamic simulations against actual operating conditions.

Through the Slovenian demo, TwinEU aims to validate a digital twin framework that can be scaled and adapted to other European systems, ensuring that the lessons learned in Slovenia benefit broader grid modernization efforts.

1.2.1 Digital twins in Slovenian power network

The concept of a digital twin in the context of the Slovenian power network involves creating a virtual replica of the physical network that mirrors its dynamic behaviour in real time. This virtual model integrates detailed dynamic representation of the transmission system with aggregated models of the distribution network. The digital twin framework serves several critical functions:

- **Real-Time Simulation and Monitoring:**
The digital twin continuously receives data from the SCADA/EMS systems, updating its state to reflect the current operational conditions. This real-time feedback loop enables the model to replicate real conditions when simulating a series of probable events, providing operators with up-to-date insights into system stability.
- **Integration of Multi-Level Models:**
A key innovation in the TwinEU approach is the merging of the detailed dynamic model of the Slovenian transmission network with a steady-state model of the surrounding observability area, supplemented with available dynamic data. This hybrid model allows for a comprehensive simulation of local phenomena (e.g., voltage sags or electromechanical oscillations) being impacted by the broader impacts of cross-border interactions.
- **Incorporation of Distributed Generation and Load Dynamics:**
Unlike traditional models that represent distribution networks as static PQ loads, the digital twin incorporates dynamic representations of DERs and voltage-dependent load models. The advanced modelling techniques enable the twin to simulate the rapid fluctuations and non-linear behaviours observed in low-voltage networks.
- **Data-Driven Parameterisation:**
The digital twin is not a static model but is continuously refined using data from extensive measurement campaigns. Parameters such as load sensitivity, generation variability, and network impedance are regularly updated based on high-resolution data, ensuring that the model remains accurate under varying operating conditions.
- **Operational Decision Support:**
The digital twin generates key stability indices—including critical clearing time, frequency nadirs, and damping ratios—which are presented via an intuitive graphical interface. These indices provide actionable insights for grid operators, enabling them to identify and mitigate potential stability issues before they arise and escalate.

By appropriately replicating the complex dynamics of the Slovenian power network, the digital twin forms the backbone of the dynamic security assessment tool. Its ability to integrate real-time data with advanced simulation capabilities ensures that the virtual model always remains a true representation of the physical grid.

The high share of renewables and decentralized generation connected to the distribution grid is changing the traditional approach of the dynamic analysis of power systems. In addition to the impact of bulk power generation on system stability, the dynamic analysis of the power system should also include the power generation connected to the distribution grid. Nowadays, the total PV generation

in Slovenia, mainly connected to the distribution grid, reaches 1.6 GW and its influence cannot be neglected.

Due to the requirements posed by complex analysis at the transmission grid level, the distribution network should be presented with an appropriate equivalent.

At this point we must disclaim that for the activities of Task 6.7 (focusing on DSA) and Task 7.7 (focusing on FFR) similar simulation models in DigSILENT Power Factory were used but nevertheless differ based on the execution of the tests and the objectives of the activities. DSA focuses on the tool development and demonstration, whereas the FFR focuses on the concept provision with its appropriate demonstration at the level which is safe, secure, and stable for the electric power system. The model used in this Deliverable 7.5 (result of the activities within the Task 7.7) will be further described in Chapter 0.

1.3 Work package and task relations

This deliverable is one of several deliverables focusing on individual demonstrations. Our work is closely related to the work packages 6 (See Task 6.7 within WP6 and its respective Deliverable D6.3) as well as the Task 7.1 within WP7.

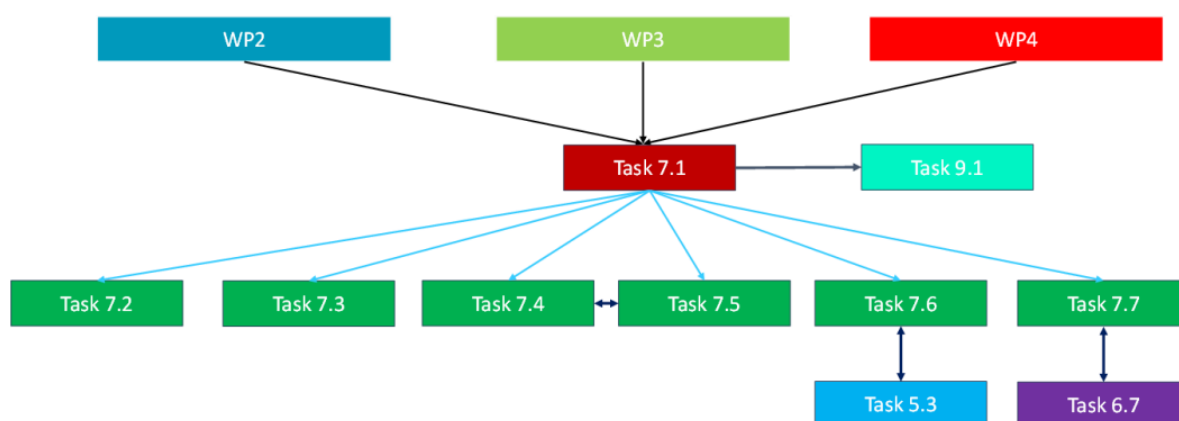


Figure 1-3 - Task relations

1.4 Objectives of the Work Reported in this Deliverable

This deliverable is built around several core objectives that address both the technical and operational challenges of modern grid ancillary services. The main objective of the Task 7.7 is the development of the concept of the fast frequency service as a new system (ancillary) service in Continental Europe. This service is provided by Fast Frequency Reserve (FFR). The objectives regarding the FFR task in the approved proposal of the TwinEU consortium were structured as following:

- Definition of technical requirements of the provision of FFR.
- Definition of the product and use case.
- Current state analysis regarding the type of devices available (power generating modules, energy storages, adaptive loads, EV...), locations (as points of common coupling with the system) and what is missing (i.e. what are the technical, regulatory, economic and market challenges for the development of such service).
- Development of the algorithm for service activation.

- Development of the testing environment, testing and result analysis.

Nevertheless, the Slovenian demo developing this FFR task went beyond the scope of these objectives in order to ensure high-quality activities and deliverable provision, also reflecting the current stage as well as the state-of-the-art development of the electric power system operation and electricity market.

1.5 Outline of the Deliverable

This document is organized into five primary chapters, each addressing a critical aspect of the work:

- **Chapter 2 – Broader aspects of the creation of the Fast Frequency Response**
Addresses the fundamental technical questions related to Fast Frequency Response, its nature, and associated challenges. It formulates development guidelines adopted in this work and positions the proposed approach within international best practice by reviewing established similar FFR implementations in selected power systems.
- **Chapter 3 – Regulatory-technical basis**
Presents the regulatory and technical framework governing power-frequency control services in Europe. It reviews relevant system operation guidelines, generator requirements, Clean Energy Package provisions, and other applicable regulatory documents that form the boundary conditions for defining and implementing an FFR service.
- **Chapter 4 – The FFR concept**
Defines the proposed Fast Frequency Response service in detail, including its product formulation, activation logic, and distinction from other frequency response mechanisms. It introduces the methodology for dimensioning FFR at both control-area and unit level, discusses market and pricing aspects, and consolidates the technical and system criteria for the service.
- **Chapter 5 – Simulations of the FFR service**
Describes the simulation environment and modelling approach used to represent the power system and the FFR service. It presents simulation scenarios for interconnected and islanded operation of the Slovenian control area and selected network configurations and summarises the key findings while clarifying limitations related to real-system testing.
- **Chapter 6 – Conclusions**
Summarises the key technical findings of the study and outlines directions for further work related to Fast Frequency Response development and deployment.

2 Broader aspects of the creation of the Fast Frequency Response

This chapter describes the comprehensive aspects and the pathway for developing and deploying the FFR service within the TwinEU Slovenian demonstration. The approach integrates advanced technical, regulatory, and market contributions of the Slovenian partners.

2.1 The crucial aspects and questions

The development of the Fast Frequency Reserve (FFR) service within the TwinEU Slovenian demonstration should be treated as a comprehensive service-design process, not only as the specification of a fast active-power response. The broader picture combines technical system needs, data availability, simulation capability, market design, stakeholder readiness, and techno-economic justification. These elements determine whether the proposed FFR service can move from a technical concept to a deployable, measurable, and sustainable system service.

Figure 2-1 provides a high-level overview of the crucial questions related to the broader meaning of the FFR service proposal, focusing on the pathway for developing and successfully deploying the FFR service.

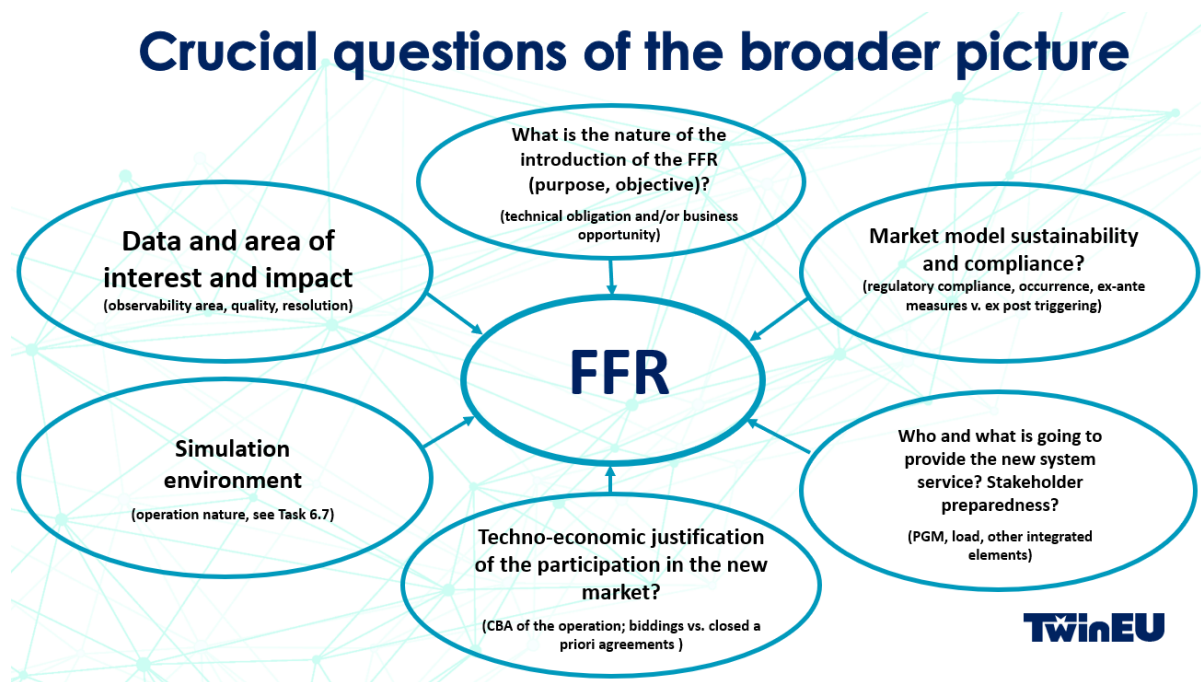


Figure 2-1 - Crucial question of the broader meaning of the FFR service proposal

The following questions are discussed in an arbitrary order and without prejudice to their relative importance.

Scope disclaimer: The aspects and questions presented in this subsection are intentionally broader than the immediate scope of the TwinEU task proposal. They are included because they are necessary for a high-level understanding of how an FFR service can be developed, positioned, and ultimately integrated into electric power system control, power system operation, and electricity market development. However, not all of these aspects are expected to be fully analysed within the present deliverable or within the formal scope of this task. The aspects that are not covered in detail should be

treated as structured input for further work, follow-up studies, future demonstrations, or later implementation phases.

A central starting point is the nature and purpose of the FFR introduction. The proposal should clearly define whether FFR is introduced primarily as a technical obligation, a market-based ancillary service, a business opportunity for flexibility providers, or a hybrid solution combining mandatory and voluntary market- or business- driven participation. This decision affects the definition of the product, the activation logic, the compliance framework, the settlement rules, and the responsibilities of participating stakeholders. The objective of the service must therefore be explicit: limiting initial RoCoF, improving the frequency nadir, and if possible, arresting the frequency deviation, supporting low-inertia operation, increasing resilience against severe disturbances, and/or enabling new flexibility resources to participate in system-support functions.

The second crucial aspect is the definition of the relevant data and area of interest. FFR is a fast service, so its successful implementation depends on sufficient observability, measurement quality, time resolution, and geographical relevance of the monitored area. The required data must support detection of frequency deviations, estimation of RoCoF, verification of activation, and ex-post assessment of delivered power and the associated short-duration energy contribution. The area of interest also must be defined carefully: the relevant observability zone may correspond to the entire national (i.e. Slovenian) control area, selected parts of the area, a demonstration feeder, or an aggregation perimeter of available participating resources needed for the purpose of the FFR demonstration. The selected area determines what can be measured, what can be validated and verified, and what operational impact can be attributed to the FFR service.

The simulation environment is another key requirement. Before practical deployment, the proposed FFR service should be tested in the most detailed modelling environment that is pragmatically feasible and that reflects the intended operation through a digital-twin representation of the relevant areas and elements of the electric power system for electromechanical transient analysis. This, may include, for example, the representation of the system inertia, the control purpose and logic of different power system elements, the disturbance scenarios, the static P-f characteristic, realistic activation delays, ramp-rate limitations, and the interaction with the wider frequency-control process during the very first electromechanical transients occurring in the system after a certain disturbance. The simulation environment should allow comparison between different realistic operating states, including high-inertia and low-inertia conditions, different disturbance severities and respective magnitudes, and different levels of available FFR. It should also support sensitivity analyses of the FFR performance. In this way, simulation becomes the link between the conceptual service definition and the practical assessment of expected system performance.

The market model and compliance concept must be defined together with the technical specification. The FFR service can only be sustainable if the product definition, qualification procedure, activation criteria, monitoring requirements, and verification rules are compatible with the intended market or regulatory framework. This includes the distinction between ex-ante requirements and ex-post triggering. Ex-ante requirements may include prequalification, declared capacity, response time, measurement capability, and availability obligations. Ex-post assessment may include verification of actual activation, delivered power, response time, and compliance with the required dynamic performance. The framework should also clarify how non-delivery, partial delivery, and measurement uncertainty are handled.

A further question concerns who is able and prepared to provide the new system service. Potential providers may include power-generating modules, controllable loads, battery systems, aggregators,

inverter-based resources, or other integrated flexibility elements. The service design must therefore evaluate stakeholder preparedness, including technical capability, communication infrastructure, control interfaces, measurement access, contractual readiness, and operational responsibility. The successful introduction of FFR depends not only on whether resources are technically capable of responding fast enough, but also on whether they can be coordinated, verified, and integrated into the operational and market processes of the control area or its respective bidding zone.

The techno-economic justification is equally important. FFR participation must be assessed against the value it creates for the power system and the cost or opportunity cost borne by the providers. This includes the comparison between participation in an open bidding process, a closed prior agreement, or another procurement mechanism. The cost-benefit assessment should consider avoided frequency-security risks, reduced need for alternative remedial measures, improved capability to operate under low-inertia conditions, and the potential business case for participating resources. The justification should also consider whether the service is needed continuously, only in selected operating states, or only during periods of reduced inertia and increased system vulnerability.

The broader design of FFR should therefore follow an integrated pathway. First, the technical purpose and operational need should be defined. Second, the relevant data, observability area, and measurement requirements should be specified. Third, the service should be tested in a simulation environment that captures the expected frequency dynamics and provider response. Fourth, the market model and compliance framework should be aligned with the technical requirements. Fifth, the provider landscape and stakeholder readiness should be assessed. Finally, the techno-economic justification should confirm whether the proposed service creates sufficient value to support implementation.

For the TwinEU Slovenian demonstration, the main value of this broader framework is that it prevents the FFR service from being developed as an isolated technical function. Instead, FFR is treated as a complete system-service proposal with clear operational purpose, measurable performance, defined provider roles, market and regulatory logic, and an explicit justification assessment for deployment. This is essential for moving from a demonstration concept to a practically implementable service design.

Where specific aspects are not addressed in the present deliverable, this should not be interpreted as reducing their importance. Rather, these open questions should be documented as a basis for further work. In particular, unresolved questions related to data access, measurement resolution, market design, compliance verification, stakeholder readiness, cost-benefit assessment, and operational integration should be considered candidates for subsequent analytical tasks, demonstration extensions, or future implementation studies.

The key questions to be resolved during FFR development are therefore:

- What is the primary objective of the FFR service: RoCoF limitation, nadir improvement, low-inertia operation support, resilience against severe disturbances, or market enablement of fast flexibility?
- Which area and data resolution are sufficient to observe, activate, and verify the service?
- Which simulation environment is adequate for testing the service before deployment?
- Which market or regulatory model can make the service sustainable and compliant?
- Which stakeholders and technologies are technically and organizationally ready to provide FFR?

- Which procurement and participation model provides a justified balance between system value and provider cost?
- Which of the above aspects are within the present TwinEU task scope, and which should be explicitly transferred to future work?

2.2 The nature of the FFR and its challenges

Fast Frequency Reserve (FFR) is introduced as a fast active-power response intended to support frequency arresting and/or deviation limitation improving the frequency stability during the first moments after a disturbance. Its main relevance, as we will see the continuation of the deliverable, increases in low-inertia operating conditions and system splits, where the initial rate of change of frequency becomes steeper and the available time for corrective action is reduced, as well as in the critical operation states (emergency, black out, restoration and resynchronisation). In this context, FFR is not only a reserve product, but also a system-control function that contributes to limiting the very first frequency excursion, improving the frequency nadir, and supporting the resilient and stable operation of systems with a high share of inverter-based and non-synchronous resources.

The development of FFR requires a clear understanding of its specific role in relation to other frequency-stability mechanisms. Natural inertial response, synthetic inertia, FFR, Limited Frequency Sensitivity Mode (LFSM) response, and the Frequency Containment Reserve (FCR) in the Frequency Sensitivity Mode (FSM) act at different time scales and through different physical or control-based mechanisms. Their interaction must therefore be explicitly considered when defining the service, because uncontrolled overlapping or poorly coordinated responses may lead to inefficient activation, over-response, rebound effects, or unclear responsibility for system support. This way the boundary or difference between a disturbance and an ancillary service can very small, which we want to prevent or avoid in any case possible.

In the TwinEU Slovenian demonstration, the analysis of FFR should therefore address both its stabilising role and its implementation challenges. These include the definition of the activation criterion, measurement and observability requirements, response speed, available capacity, verification of delivered power, and coordination with existing frequency-control processes.

The following subsections discuss the role of FFR in supporting frequency stability in low-inertia conditions and its distinction from related mechanisms such as natural inertial response, synthetic inertia, LFSM, and FCR.

2.2.1 Role of FFR in Supporting Frequency Stability in Low-Inertia Conditions

Fast Frequency Response (FFR) plays a critical role in maintaining frequency stability in power systems with a high penetration of inverter-based renewable energy sources and reduced synchronous inertia. In the future power systems with high share of RES, the displacement of synchronous generators by wind, solar PV, and HVDC-connected resources reduces the aggregate system inertia constant, thereby increasing RoCoF following disturbances. Under such conditions, the natural inertial response of synchronous machines becomes insufficient to limit the initial frequency decline, and the frequency nadir may reach critical thresholds before LFSM can fully activate. Declining inertia will require new fast-acting reserves to complement traditional frequency containment

mechanisms. FFR provides rapid active power injection within approximately 0.1–2 seconds², thereby stabilizing the frequency trajectory during the critical early period following a disturbance. This rapid intervention of FFR reduces the maximum frequency deviation, limits the activation of Load Frequency Demand Disconnection (LFDD), and improves overall system resilience.

Figure 2-2 conceptually illustrates the role of FFR in supporting frequency stability immediately after an active-power disturbance. At $t = 0$, the system is exposed to an imbalance that initiates a frequency deviation. In the absence of sufficiently fast corrective action, the frequency decreases rapidly, and the system moves towards an unfavourable nadir. This initial phase is especially critical in low-inertia conditions, where the rate of change of frequency (RoCoF) is high and the available time for intervention is limited.

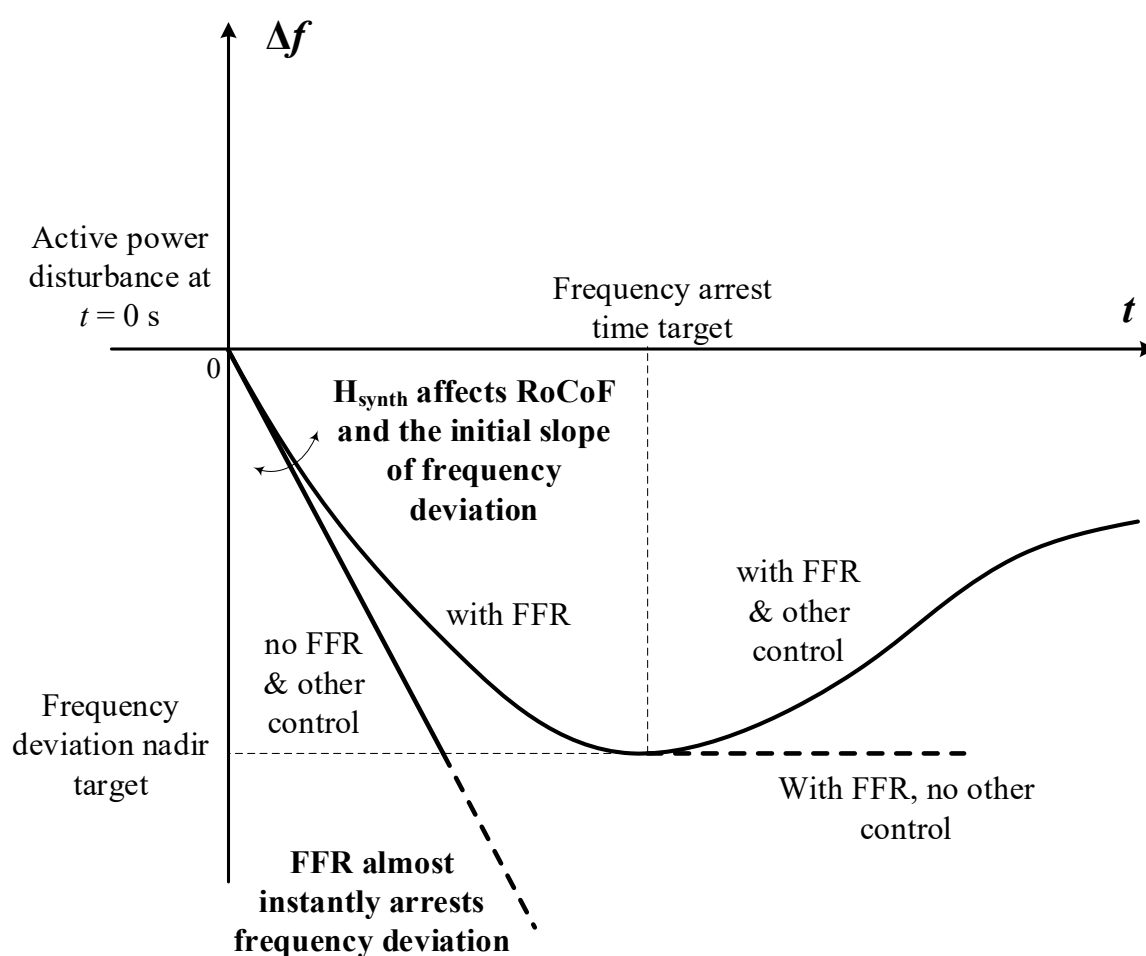


Figure 2-2: The idea of the FFR

The figure highlights that the initial slope of the frequency deviation is strongly influenced by the effective system inertia, including the contribution of synthetic or emulated inertia. A higher effective inertia reduces the initial RoCoF and therefore slows down the frequency decline. This does not by itself remove the disturbance, but it increases the time available for control actions and improves the conditions for activating fast reserves. In this sense, synthetic inertia and FFR are complementary: the

² The exact response times are discussed later in the deliverable within the main chapter “The FFR concept”

former primarily affects the first slope of the frequency trajectory, while the latter provides fast active-power support intended to arrest the ongoing deviation.

The core purpose of FFR is to act quickly enough to slow down and, ideally, arrest the frequency deviation before the system reaches an unacceptable nadir. As indicated in the figure, FFR changes the natural course of the frequency trajectory by reducing the depth of the frequency excursion and by shifting the system response towards a frequency-arrest target. This means that the service is primarily aimed at the very first electromechanical transients, where the time window for effective intervention is short and the operational value of a rapid response is the highest.

The figure also distinguishes between different post-disturbance outcomes. If FFR is activated but no additional control layers are present, the frequency deviation may be arrested and then maintained approximately at a new quasi-steady level. In contrast, if FFR is followed by other control actions, such as slower frequency-control mechanisms, the system can subsequently recover from the arrested deviation and move back (restore) towards the nominal operating point. This illustrates an important principle: FFR is not necessarily intended to restore frequency on its own, but rather to stabilise the system during the earliest stage of the event and to create the time and conditions required for other control layers to take over: FCR, aFRR, mFRR and/or RR.

From the operational perspective, the figure therefore positions FFR as an intermediate fast-response layer between inertial phenomena and slower reserve-based frequency control. Its practical value is greatest in systems with reduced synchronous inertia, where conventional inertial buffering is weaker and where the initial frequency decline can be too steep to be managed effectively by slower reserves alone. In such conditions, FFR becomes a key enabler for maintaining stable operation, reducing the risk of deep frequency excursions, and improving resilience against severe disturbances.

Overall, the figure supports the interpretation that the role of FFR is not limited to the delivery of fast active power as an isolated product. Rather, FFR should be understood as a dedicated short-timescale stabilizing service whose purpose is to support frequency arrest, improve the nadir, and facilitate the coordinated action of the wider frequency-control framework. This makes FFR particularly relevant in the context of modern power systems with increasing shares of inverter-based resources and changing inertia characteristics.

To summarise from the system perspective of view: In the future power systems increasing penetration of non-synchronous generation leads to a measurable increase in frequency volatility and faster frequency dynamics, requiring faster response services such as FFR. FFR becomes particularly important during periods of low demand and high renewable generation, such as summer nights with high wind penetration or high solar output combined with low thermal generation. Under these conditions, system inertia may fall below critical operational thresholds (e.g., below approximately 100–150 GWs inertia equivalent in CE), significantly increasing the risk of excessive RoCoF and deep frequency nadirs. FFR provides a controllable, predictable, and dispatchable substitute for part of the stabilizing effect traditionally provided by synchronous machines.

Frequency deviations³ exceeding ± 200 mHz can occur regularly under contingency conditions in periods of low inertia power system operation, while deviations exceeding ± 400 mHz occur less frequently (mainly during reference incident) but represent critical stability events. Deviations beyond ± 800 mHz are rare but correspond to severe disturbances or system separation events (power system split). FFR is specifically designed to prevent frequency excursions from reaching such extreme levels

³ At the points of common coupling, at the crucial system busbars or at the TSO's control centres, depending on the system

by providing rapid active power injection during the initial seconds following a disturbance and before activation of first step of LFDD.

2.2.2 Distinction between the natural Inertial Response, Synthetic Inertia, FFR and primary reserve response

Natural inertial response is an inherent physical property of the rotating machines, primarily the synchronously connected machines. It results from the exchange of kinetic energy stored in the rotating masses of Synchronous Power Generating Modules (SPGMs) when the system is exposed to an active-power imbalance. Immediately after a disturbance, the rotor speed of synchronous machines starts to change, and this electromechanical behaviour contributes to opposing the initial frequency change. Therefore, natural inertial response occurs without measurement, communication, or dedicated control activation. Its main system-level effect is to reduce the initial rate of change of frequency, i.e. the initial RoCoF.

Synthetic inertia is a control-based response of converter-interfaced resources that emulates part of the inertial behaviour by rapidly adjusting active power in response to frequency or RoCoF-related signals. In the context of this analysis, Grid-Forming Modules (GfMs) are converter-based technology for providing a synthetic-inertia-type response, because their control structure can directly support voltage and frequency formation. It may be provided by inverter-based resources with GFM capabilities such as Battery Energy Storage Systems (BESS), HVDC systems, and other RES such as wind parks and PVs, but only if the right conditions are met. Unlike natural inertia, synthetic inertia is not an inherent physical property of rotating masses, but an implemented control function. Its performance therefore depends on measurement quality, control delay, converter capability, available energy, current limits, and system-strength conditions.

Grid-forming modules, unlike the Grid-following modules (GfMs) are generally better suited to provide a synthetic-inertia-type response with stronger grid-supporting characteristics, because they can contribute to voltage and frequency formation through their internal control behaviour. In a true manner of synthetic inertia, only grid-forming modules are capable of synthetic inertia provision. Grid-following modules may also provide fast, but not instant or almost instant, derivative-based active-power response. This response is delayed (lagged), measurement-based and may be affected by Phase-Locked Loop (PLL) dynamics, filtering, weak-grid conditions and control interactions. For this reason, grid-following derivative response should be clearly distinguished from natural inertial response and from GfMs synthetic inertia.

Fast Frequency Reserve (FFR) differs from both natural and synthetic inertia. FFR is not primarily or necessary proportional to the frequency derivative. Instead, it is a fast active-power response dependent on frequency deviation and time, including activation thresholds, delays, ramp limits, saturation levels, and allowed activation and/or deactivation durations, independently or depending on the activation of the other slower frequency ancillary services. It may be represented conceptually as $P_{FFR} = P_{FFR}(\Delta f, t)$.

FFR typically activates after the initial inertial phase, but before primary droop control activation commence is effective. We already mentioned its purposes: mainly to provide fast active-power support in order to improve the frequency nadir and help arrest or limit the ongoing frequency deviation. Unlike inertial response, FFR is a defined service or control function, and its performance must therefore be specified, measured, validated and verified, and coordinated with other frequency-control processes.

Fast Frequency Response differs from synthetic inertia in that it provides active power injection based on frequency deviation thresholds and/or is a function time-frequency deviation function rather than a function of frequency derivative. Fast Frequency Response typically activates slightly later than synthetic inertia but provides sustained active power injection over longer durations and provides sustained frequency stabilization.

Primary reserve response is associated with droop-based frequency control in Frequency Sensitive Mode (FSM, frequency deviation within ± 200 mHz around the nominal 50 Hz) and Limited Frequency Sensitive Mode (LFSM, frequency deviation beyond ± 200 mHz around the nominal 50 Hz). FSM is relevant for proportional response to frequency deviations within the normal operating range, while LFSM is intended for larger deviations beyond defined thresholds. Frequency Containment Reserve (FCR), where applicable, can be understood as the procured reserve process associated with primary frequency containment. In comparison with inertial response and FFR, primary droop control acts on a slower timescale and provides sustained support. Its role is to contain and stabilize the frequency at a new operating point, but it does not (necessarily) restore the frequency to the nominal value by itself, for which we need frequency restoring mechanisms such as Frequency Restoration Process provided by Frequency Restoration Reserves (automatic — aFRR and manual — mFRR).

The distinction between these mechanisms is important for the FFR service definition. Natural inertia and synthetic inertia mainly influence the initial RoCoF. FFR acts in the early post-disturbance interval to improve the nadir and help limit the ongoing deviation. Primary droop control then provides sustained containment. These functions are complementary, but they are not interchangeable.

Figure 2-3 provides a simplified time-domain interpretation of the main frequency-support mechanisms relevant for the development of FFR. The non-linear time axis separates the response into three conceptual intervals:

- The first interval, 0–0.1 s, represents the immediate inertial phase. In this period, the response is dominated by natural inertia from SPGMs and synthetic inertia from GFMs. These responses are associated with the initial RoCoF and are represented as proportional to the negative frequency derivative.
- The second interval, 0.1–2 s, represents the FFR activation phase. FFR is shown as a fast, time-limited response that depends on both frequency deviation and time. Its purpose is not to replace inertia, but to provide fast active-power support after the inertial phase and before primary droop control becomes dominant.
- The third interval, 2–30 s, represents the progressive activation of primary droop control in FSM or LFSM. This response is slower than FFR but sustained. It stabilises the frequency at a new level and enables the gradual deactivation of FFR. The figure therefore shows FFR as a bridging service between immediate inertial effects and slower primary frequency containment.

Figure disclaimer

Figure 2-3 is a conceptual illustration and not a calibrated dynamic model. The shapes, amplitudes, and exact timing of the curves are indicative only. Actual response behaviour depends on system inertia, disturbance size, converter control design, measurement and communication delays, FFR product definition, activation thresholds, ramp-rate limits, saturation constraints, FSM/LFSM droop settings, and the operating state of the power system.

The time axis is schematic and non-linear. The intervals 0–0.1 s, 0.1–2 s, and 2–30 s should be interpreted as functional time ranges rather than strict universal limits. The figure is intended for service-positioning and explanatory purposes, not for quantitative validation of frequency stability or reserve adequacy. The inertial response is purposely shown only in the first post-disturbance moments.

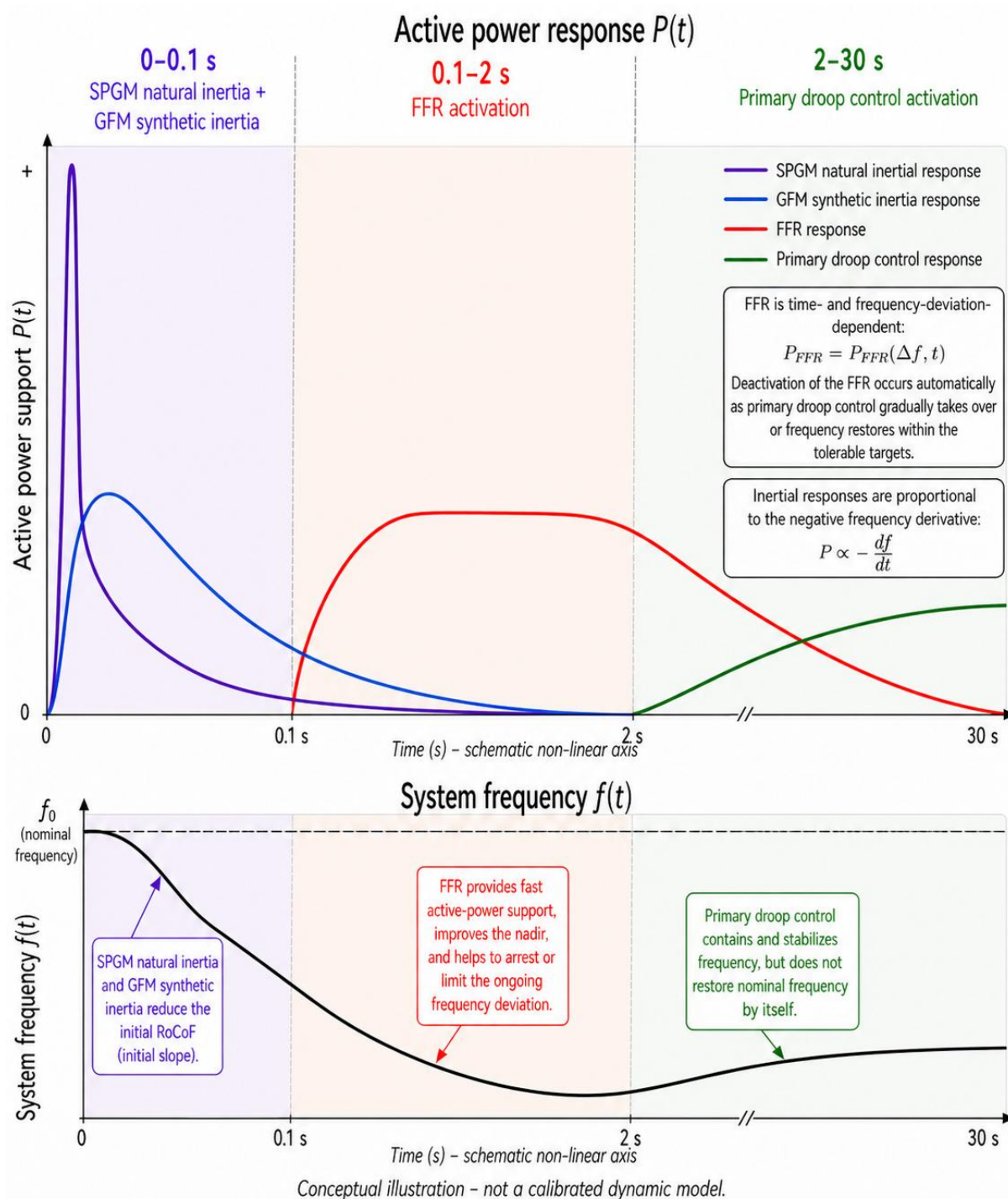


Figure 2-3: Conceptual distinction between inertia-related responses, FFR and primary (droop control) responses in FSM or LFSM

2.3 Our FFR development guidelines

For the development of the FFR service concept, the task objectives were complemented by a set of internal guiding principles. These principles were used to keep the proposed service technically meaningful, practically implementable, and suitable for further assessment within the TwinEU Slovenian demonstration.

The FFR service should be designed as a **simple and transparent** service. This means that the basic product logic should be understandable, **scalable**, and applicable to different classes of technically capable providers. The service should be **technology-neutral and non-discriminatory**, while still allowing classification according to the actual technical capability of each provider. Where relevant, the service should also be **symmetrical**, meaning that it should be conceptually applicable to both under-frequency and over-frequency situations.

FFR provision should be based on **continuous availability**, but its **activation must be carefully selected**. A continuously available service does not imply continuous activation. Instead, it means that qualified resources are technically ready to provide fast active-power support when the activation conditions are met. The activation logic must therefore be defined in a way that supports the security and **stability of the electric power system without creating unnecessary or inefficient activations**.

The service should also be **precise in time**. Since FFR is intended to support the system during the earliest stage after a disturbance, the relevant measurement, activation, and verification processes should be considered at millisecond-scale resolution where technically feasible. This is important for distinguishing FFR from slower reserve products and for verifying whether the required response has actually been delivered within the relevant time window.

A further guideline is that FFR should have a **short activation duration**. FFR is not intended to replace slower frequency-control mechanisms or long-duration balancing products. Its role is to provide fast and time-limited support during the initial frequency transient, improve the frequency nadir, and help arrest or limit the ongoing frequency deviation until primary droop control or other slower mechanisms can take over. Therefore, the service should be described through clearly defined parameters such as activation time, duration, delivered power, activation threshold, RoCoF sensitivity if and where relevant, delivered energy, and ramping behaviour.

Although FFR is technically activated locally through resources connected to specific parts of the system, its relevance is broader. FFR provision may contribute to a **market of wider character**, potentially aligned with Continental European frequency-stability needs, while still having a **local operational influence**. This dual nature is important: the service may be defined and coordinated in a wider system context, but its actual impact depends on where the resources are connected, and how they interact with the local and national control-area dynamics.

The development guidelines can therefore be summarised as follows (Figure 2-4):

- **Simplicity:** the service should be scalable, transparent, non-discriminatory, and technically neutral, while allowing classification according to provider capability.
- **Continuity:** resources should be continuously available for activation, but the actual activation should occur only under carefully defined system conditions.
- **Precision:** activation, delivery, and verification should be assessed with sufficient time resolution, preferably at millisecond scale where required by the service definition.

- **Short duration:** FFR should be a fast, if necessary, time-limited service intended for the initial frequency transient, not a substitute for slower frequency-control or balancing mechanisms.
- **Wider market character with local influence:** the service may support broader frequency-stability objectives, while its technical effect remains dependent on local observability, location, and provider behaviour.

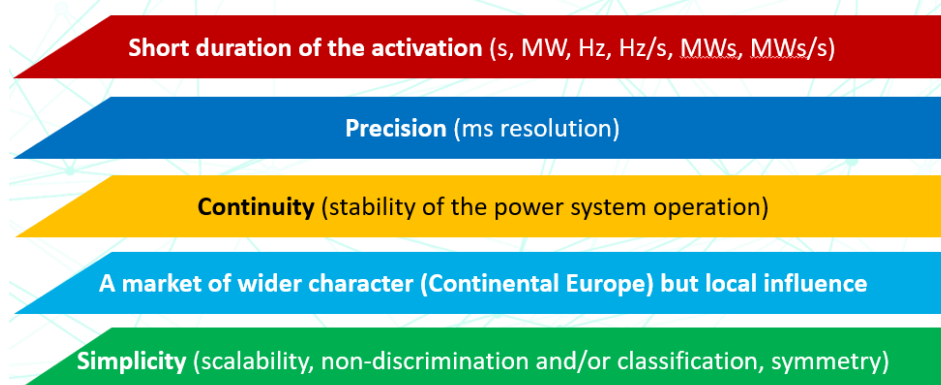


Figure 2-4 - FFR development guidelines

2.4 International best practice examples

This chapter reviews selected international examples of FFR and comparable fast frequency-control services. The analysis focuses on the technical design of the services, their market and procurement arrangements, and the technologies used for provision of such services. The Nordic region, Australia, Great Britain, Ireland and Northern Ireland, Canada, and Germany were considered to identify relevant approaches, common design principles, and potential lessons for the further development of FFR in Continental Europe in the light of the TwinEU scope.

International practice confirms that fast frequency services are not implemented through a single universal product. Their technical parameters and procurement arrangements reflect the size, configuration and strength of the synchronous area, particularly the prevailing inertia, the credible disturbances, the degree of interconnection, the available technologies and the maturity of the national ancillary-service market.

The Nordic FFR product is procured specifically for low-inertia hours and is activated autonomously from local frequency measurements. Australia has integrated one-second raise and lower services into the existing co-optimised FCAS markets. Great Britain uses a portfolio of dynamic response products that distinguishes post-fault containment from pre-fault moderation and routine regulation. Ireland and Northern Ireland combine the existing DS3 FFR product with an evolving day-ahead procurement framework and differentiated sub-second response categories. Alberta, Canada, has developed frequency-triggered FFR around the risk of critical inertia loss and islanded operation, and is moving from pilots and fixed-term contracts towards recurring market-based procurement and a highly available FFR product. Germany has introduced market-based procurement of instantaneous reserve, which is not FFR in the strict sense, but a complementary inertia-related service delivered by very fast synchronous machines (i.e. flywheels) and grid-forming converters.

Across the reviewed systems, the most suitable technologies are battery energy storage systems (BESS), fast controllable demand response, inverter-based generation with appropriate controls, HVDC facilities and, for inertia-related products, synchronous machines and grid-forming converters.

BESS is particularly prominent because it combines extremely fast active-power control, bidirectional operation, and also very accurate performance verification. Nevertheless, technology eligibility is generally performance-based and subject to prequalification, metering, monitoring and availability requirements.

The principal conclusion is that international practice should be used as a source of design principles rather than copied directly. We concluded that the future FFR concept for Continental Europe must be developed for the conditions of the relevant synchronous area and control area, with explicit coordination of activation thresholds, response time, duration, capacity, locational distribution, interaction with FCR market and system defence measures, and the chosen procurement model.

Disclaimer: The international examples presented in this section reflect information available at the time of preparation of the deliverable. Technical requirements, procurement arrangements, market rules and eligible technologies may have changed subsequently, and not every national detail could be independently verified within the scope of this work. The examples should therefore be interpreted as an indicative overview of relevant design approaches in the control areas rather than as a complete or legally binding description of the current arrangements in each control area. The analysis reflects information available during preparation of the deliverable and was checked against selected official sources available in July 2026.

2.4.1 Nordic practice

The Nordic synchronous area has long treated low inertia as an explicit operational condition. Fast Frequency Reserve was introduced to prevent the frequency from falling below the operational security limit following a reference incident when rotational energy is low. The required volume is therefore not fixed throughout the year; it is linked to the forecast inertia level and the size of the credible disturbance [4], [5], [6], [7], [8], [9], [10], [11], [12].

FFR is distinct from the Nordic Frequency Containment Reserve for Disturbances. FFR acts earlier and is intended to support the first part of the frequency excursion in low-inertia conditions. FCR-D provides the subsequent containment response over a slower time scale. The two services are complementary and may be offered through combination bids where the same resource is prequalified for both products.

Activation is autonomous and based on local frequency measurement; the TSO does not transmit a real-time activation command. The provider selects one of several combinations of activation threshold and maximum full-activation time. A lower activation threshold permits a longer response time, while a deeper frequency deviation requires a faster response. This creates a transparent trade-off between early activation and delivery speed.

Fingrid procures FFR through a national hourly capacity market for selected hours in which low inertia creates a need for the product. Bids are submitted day-ahead, and the hourly capacity price is set by the most expensive accepted bid. Procurement volumes vary with the expected operating condition rather than being maintained at a constant annual level [13].

Similarly, in the DK2 bidding zone of eastern Denmark, the need for FFR in DK2 is continuously forecasted and published on Energi Data Service. The hourly forecast for the upcoming operating day (D+1) is the amount that will be procured in the auction for the upcoming operating day. Energinet procures FFR on national daily auctions on an hourly basis with marginal pricing settlement per hour.

Capacity is settled based on marginal pricing. No accounting of delivered energy volumes is made. Deliveries are settled as normal imbalances [14].

FFR (Fast Frequency Reserve) mitigates large frequency drops by regulating assets at very high speed. The sole purpose of FFR is to reduce instantaneous and large frequency deviations. FFR works by consumption or generation units monitoring the frequency and responding when the frequency drops to 49.7 Hz or below. FFR is procured only in DK2.

Participation requires unit-level prequalification and a market agreement. Combination bids with FCR-N or FCR-D Up improve the opportunity cost management of flexible resources and reduce unnecessary fragmentation of reserve capacity. The Nordic model therefore combines a clearly defined technical product with short procurement horizons and system-condition-dependent volumes.

Table 2-1: FFR in the Nordic region

Design element	Current practice / interpretation
Activation principle	Automatic local response to underfrequency only during low-inertia operating hours.
Full-activation alternatives	49.7 Hz within 1.3 s; 49.6 Hz within 1.0 s; or 49.5 Hz within 0.7 s.
Minimum delivery	At least 5 s where deactivation is limited to 20% of capacity per second; otherwise at least 30 s.
Repeatability	The resource must be ready for reactivation within 15 minutes.
Relationship with FCR-D	FFR supports the initial excursion; FCR-D provides slower disturbance containment.

The product is technology-neutral, provided that the resource can measure frequency locally, activate autonomously and pass the prequalification tests. BESS, controllable demand, industrial loads, generating units and suitable inverter-based resources can participate. BESS is particularly suitable because it can provide a rapid and repeatable response with limited energy requirements, while flexible demand can provide fast upward reserve through consumption reduction.

Relevance for the TwinEU FFR concept

The Nordic practice demonstrates the value of linking procurement to the actual inertia condition, using autonomous local activation and coordinating FFR with slower frequency-containment products. It also shows that a single technical requirement may be expressed through several equivalent threshold-time combinations. Direct replication is nevertheless inappropriate because the Nordic frequency-security criteria, reference incidents and market structure differ from those of Continental Europe.

2.4.2 Australian practice

The Australian National Electricity Market covers a geographically extensive and electrically elongated system with increasing inverter-based generation. Frequency Control Ancillary Services (FCAS) are used to correct small imbalances and to arrest frequency following major contingencies. The relevant fast products are the contingency raise and lower services, particularly the one-second Very Fast FCAS markets and the six-second Fast FCAS markets [15], [16], [17].

Raise services increase net injection or reduce demand after an underfrequency event. Lower services reduce net injection or increase demand following an overfrequency event. The product set is therefore explicitly symmetric and integrated with the broader hierarchy of contingency frequency control.

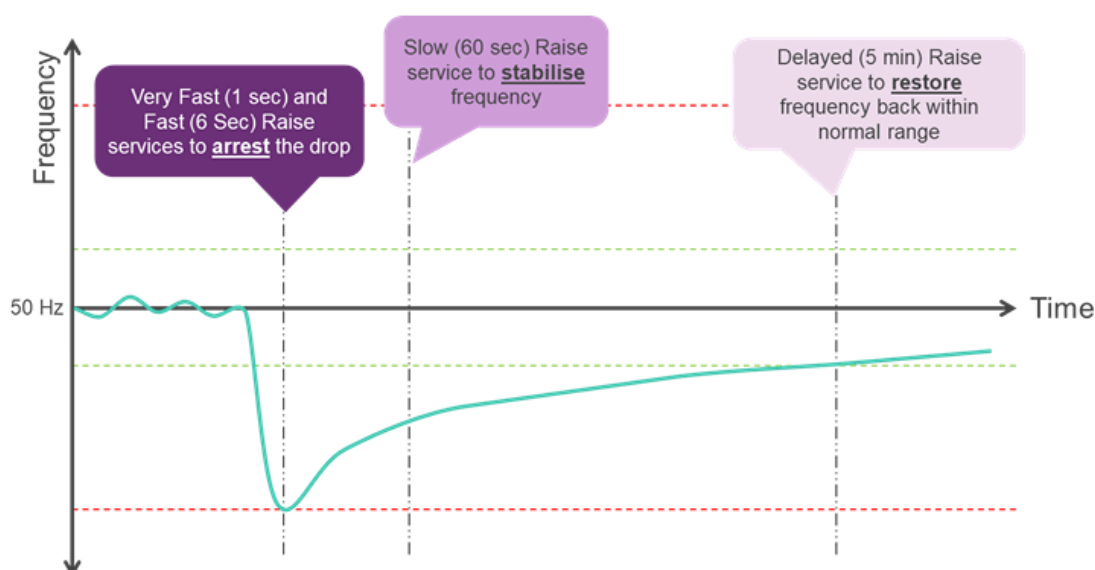


Figure 2-5: Contingency frequency control through coordinated FCAS products, adapted from the AEMO materials

Very Fast FCAS is designed to provide measurable response within the first second after a contingency. It is followed by slower six-second, sixty-second and delayed contingency services, which progressively replace the initial response. The technical concept is therefore based on a sequence of products rather than a single service expected to cover the complete frequency event.

The amount of service that a facility can provide depends on its operating point. A generator, storage facility or load may have different upward and downward capabilities depending on its energy dispatch, technical limits and ramping capability. The response must be verified against the Market Ancillary Service Specification and the registered capability of the facility.

AEMO has separate raise and lower markets for each FCAS time category. FCAS is co-optimised through the National Electricity Market Dispatch Engine. For each dispatch interval, the engine enables sufficient service to satisfy the regional requirement while respecting energy dispatch, network and unit capability constraints.

Providers submit availability and prices through FCAS bids. The capability is represented by an FCAS trapezium, which describes how much service can be delivered at different energy operating points. Accepted bids are enabled in economic order, and the marginal accepted bid sets the clearing price for the service. This arrangement integrates fast frequency response directly with the energy market and makes the opportunity cost of headroom visible.

BESS is the leading technology for Very Fast FCAS because it can precisely and rapidly change active power in both directions. Aggregated demand, flexible industrial loads, hydro units, gas turbines, wind and solar plants with available headroom may also participate if and where they satisfy registration and measurement requirements. Aggregation is important because it allows smaller resources to meet market and telemetry requirements through a coordinated portfolio, which could be an obstacle in Continental Europe due to the distribution network constraints.

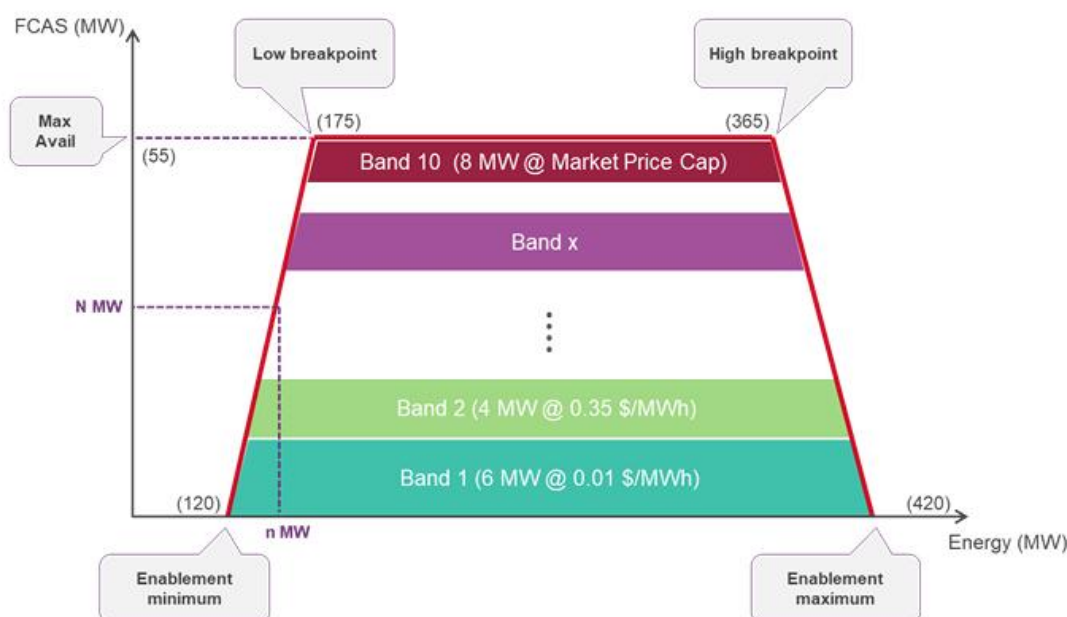


Figure 2-6: Generic FCAS trapezium linking ancillary-service capability to the energy operating point, adapted from the AEMO materials

Relevance for the TwinEU FFR concept

Australia demonstrates the benefits of symmetric raise and lower products, co-optimization with the energy market and explicit representation of the provider's feasible operating region. The main transferable principle is that contracted FFR capacity must remain technically deliverable at the actual operating point. The detailed FCAS market design, however, reflects the structure of the NEM and cannot be transferred directly to a single Continental European control area.

2.4.3 Great Britain practice

Great Britain has developed a portfolio of dynamic frequency-response services to manage declining inertia, large credible disturbances and increasing operational variability. Rather than using one generic FFR product, the National Energy System Operator distinguishes between post-fault containment, fast pre-fault moderation and slower continuous regulation [18], [19].

Dynamic Containment is the principal post-fault product and is intended to contain frequency after a significant event. Dynamic Moderation provides fast pre-fault response during volatile conditions, while Dynamic Regulation provides slower routine correction around nominal frequency. The separation of products allows the operator to procure response according to the prevailing system states and needs.

The British services are defined through measurable power delivery rather than only through controller setpoints. Providers must demonstrate the response of the complete unit or aggregated portfolio, including metering, communications, state-of-energy management and the ability to sustain delivery for the specified period.

Dynamic Containment, Dynamic Moderation and Dynamic Regulation are procured through competitive auctions on the EAC platform. Providers must register and prequalify assets before participating, and auction results are published through the NESO data portal. Performance monitoring and settlement are integral parts of the service design.

Table 2-2: Dynamic ancillary services in Great Britain

Design element	Current practice / interpretation
Dynamic Containment	Post-fault service; response initiation within 0.5 s, full delivery within 1 s, and 15-minute duration for energy-limited providers.
Dynamic Moderation	Fast pre-fault service; response initiation within 0.5 s, full delivery within 1 s, and 30-minute duration.
Dynamic Regulation	Slower pre-fault regulation; response initiation within 2 s, full delivery within 10 s, and 60-minute duration.
Activation	Continuous proportional response to measured frequency according to the relevant service curve.
Verification	Unit testing, operational metering, availability data and detailed performance monitoring.

The market is characterized by short procurement horizons and frequent competition. This supports price discovery and allows the volume requirement to be adjusted as forecasts of inertia, demand and the largest credible losses change. NESO continued to revise the service terms and procurement rules in 2026, illustrating that fast-response products require continuous operational and market refinement.

BESS have become a major provider because the services require rapid, accurate and bidirectional control. Other eligible technologies include flexible demand, aggregated distributed resources, hydro, conventional generation, interconnectors and inverter-based generation with sufficient headroom. Technology is secondary to verified performance, state-of-energy management and compliance with the metering requirements.

Relevance for the TwinEU FFR concept

Great Britain demonstrates that frequency response can be separated by operational purpose: post-fault containment, pre-fault moderation and routine regulation. For TwinEU, the principal lesson is to define clearly whether FFR is an event-driven post-fault product or a continuously active modulation service. The proposed Slovenian concept is closer to post-fault containment, but with a shorter intended delivery period and a different activation characteristic.

2.4.4 Irish and Northern Irish practice

Ireland and Northern Ireland operate a relatively small synchronous island with high non-synchronous renewable penetration. This creates a strong need for fast and accurately verified frequency response. The DS3 System Services arrangements introduced FFR as a dedicated product, while the Future Arrangements for System Services are developing a more competitive day-ahead procurement framework.

The existing FFR concept requires additional active-power output or demand reduction to become available during the first seconds after an event. The response is assessed not only by its full-activation time, but also by its sustained contribution and the subsequent energy recovery. This is important for energy-limited resources because a rapid initial injection should not be followed by an uncontrolled withdrawal that negates the benefit.

Under the DS3 arrangements, the standard FFR product is fully available within two seconds, with performance assessed over the early post-event period. Faster response has been encouraged through performance scalars. The future FASS/DASSA design has considered three enhanced subcategories that differentiate resources capable of full activation within approximately 150 ms, 300 ms and 1 s. These categories recognize that sub-second response has additional system value [20].

The proposed reserve trajectory defines the frequency range between the activation trigger and full response. This approach separates the frequency threshold from the required power slope and allows different technologies to provide a comparable service. The trajectory can be implemented as a dynamic proportional response or, for suitable resources, as a static triggered response subject to volume and coordination limits.

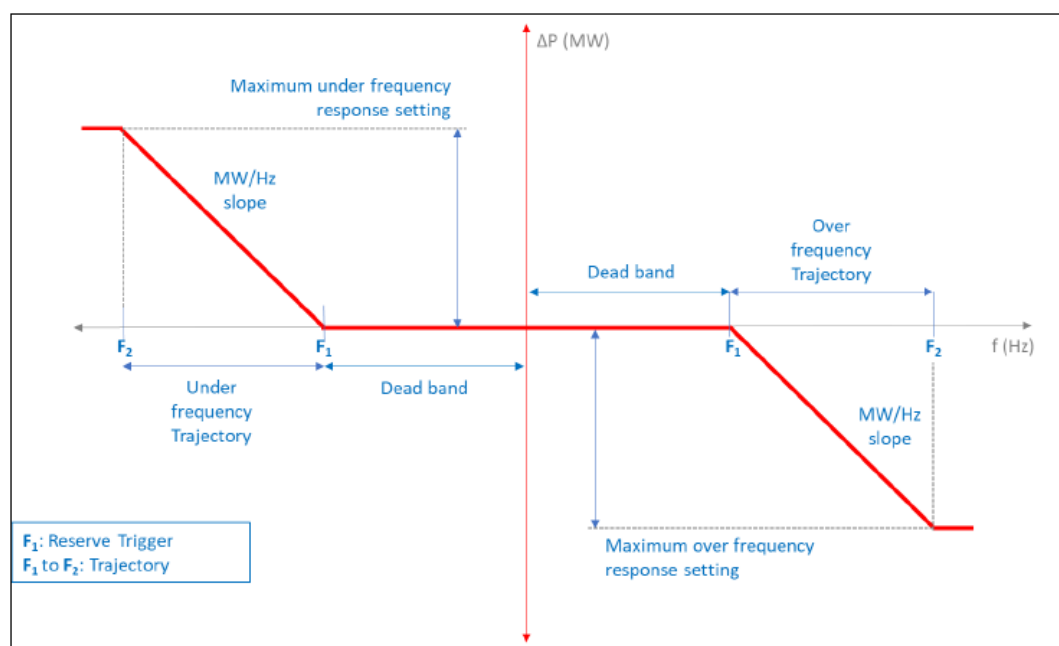


Figure 2-7: Illustration of the reserve trigger and frequency-response trajectory, adapted from the EirGrid and SONI materials

The regulated DS3 arrangements have relied on qualifications, contractual service rates and performance scalars. The future DASSA framework is intended to procure system services through a day-ahead auction with defined trading periods, bid price limits, volume rules and locational considerations. The reform aims to improve competition while retaining the ability of the TSOs to secure the technical mix required for system operation [21].

The Irish and Northern Irish approach also addresses concentration risk. Large volumes of fast static response activated at the same threshold may create overshoot or oscillatory behaviour. Product design therefore includes controlled trajectories, deadbands, qualification limits and potential restrictions on the volume provided by a single unit or portfolio.

Eligible technologies include BESS, demand-side units, HVDC interconnectors, wind generation, flexible loads, flywheels, supercapacitors and conventional generation with suitable controls. BESS and fast demand response are particularly relevant for the enhanced sub-second categories. Wind and other inverter-based resources may provide dynamic response where headroom and energy recovery are appropriately managed.

Relevance for the TwinEU FFR concept

The Irish and Northern Irish practice is the closest international reference for a short-duration, sub-second FFR product. The strongest transferable elements are differentiated response-speed categories, performance-based remuneration and limits on concentrated static response. The exact thresholds and categories must nevertheless be recalculated for Continental European frequency behaviour and the Slovenian control area.

2.4.5 Canadian practice

The reviewed Canadian example is Alberta. The Alberta interconnected electric system is linked to the Western Interconnection through the British Columbia and Montana. Under weak interconnection or islanded operation, the loss of a large generator or an importing inertia can produce a rapid frequency decline and a risk of underfrequency load shedding. FFR is therefore closely linked to inertia availability and island system security.

The AESO pilot initially required response within 12 cycles, that is approximately 0.2 s, after detection of 59.5 Hz. Because the participating facilities could not consistently satisfy that condition, the pilot was continued with an alternative requirement of response within 18 cycles, approximately 0.3 s, at 59.6 Hz. This is a useful example of the need to validate proposed technical parameters against actual provider capability before finalizing a product [22].

The Alberta product differs from short-duration European FFR concepts, as provided in the rest of the deliverable, because it also requires prolonged support or availability to complement contingency reserves and maintain schedules of the units with significant inertia. Distribution-connected resources face additional requirements because a rapid active-power injection can create voltage excursions and conflict with distribution ramp-rate limits. Detailed electromagnetic-transient studies and coordination with the distribution network operator are therefore needed.

The original pilot used a combination of availability and event-response payments. Alberta subsequently moved to competitive fixed-term procurement. In 2024, the AESO contracted 603 MW of interconnected FFR from twelve providers using loads, energy storage and hybrid facilities. A separate island service procurement secured 190 MW from nine facilities for weakly interconnected and island conditions.

The service has therefore been procured primarily through competitive contracts rather than a continuously cleared spot market. In 2026, the AESO was developing two next-stage arrangements: recurring Market-Based FFR procurement for existing capable resources and FFR+, a highly available contracted product. The FFR+ design remained under stakeholder development, with procurement targeted for the second half of 2026.

The Alberta procurements are technology-agnostic and have included BESS, controllable loads and hybrid facilities. BESS is important for the proposed highly available FFR+ product because it can provide rapid local response and maintain a defined energy reserve. Load resources remain valuable because they can reduce demand almost instantaneously without requiring sustained energy injection. Distribution-connected resources may participate only where network impacts, telemetry and protection requirements are adequately addressed, in particular coordinated with the voltage control in the distribution system.

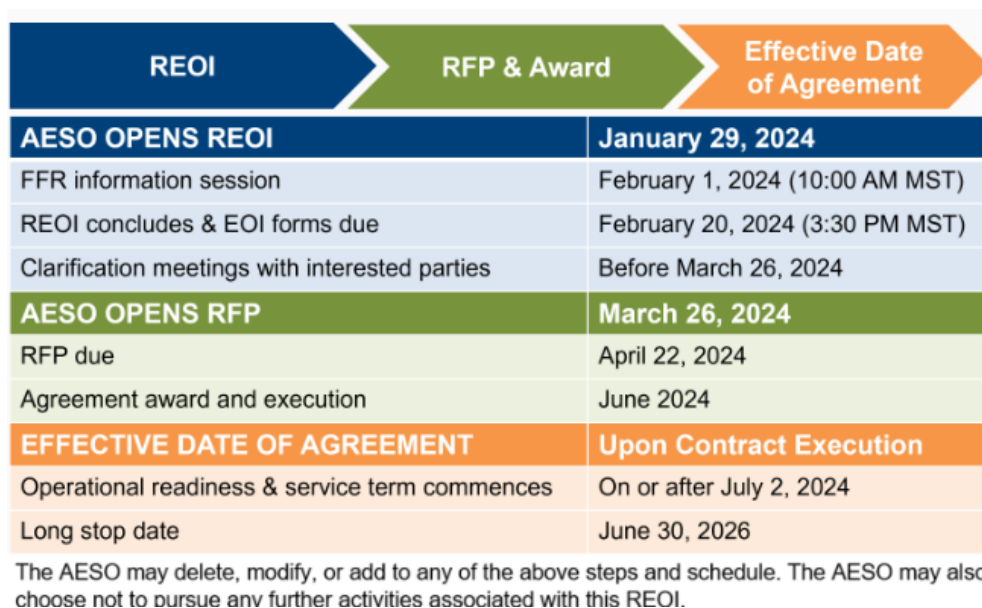


Figure 2-8: Two-stage AESO procurement process for interconnected FFR

Relevance for the TwinEU FFR concept

Alberta demonstrates that FFR may be designed around a specific system-security problem, such as intertie loss, rather than as a generic reserve product. It also highlights the practical need to adjust response thresholds after field testing and to distinguish between fast activation and prolonged availability. For TwinEU, the main lesson is that the procurement model must reflect the disturbance being covered and the role of existing contingency reserves.

2.4.6 German practice

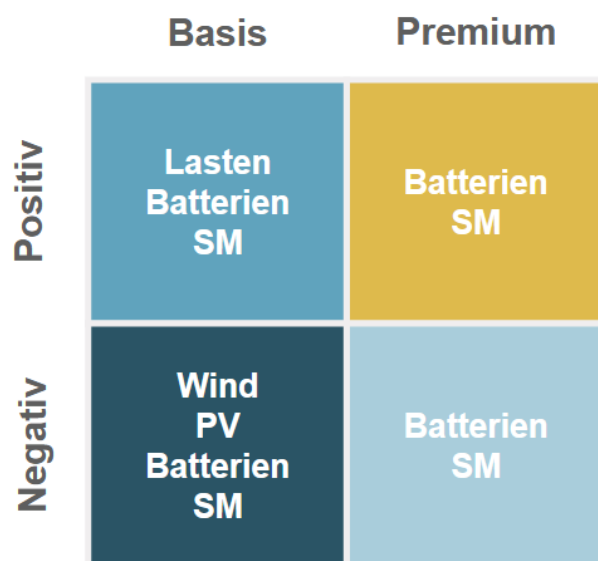
Germany provides an important comparison, but its new product should not be classified as FFR in the strict sense. The German instantaneous reserve, or *Momentanreserve*, is an inertia-related system service that reacts directly to the frequency gradient. Its purpose is to continuously limit RoCoF at the source of an active-power imbalance. By contrast, the Slovenian TwinEU FFR concept is activated by frequency deviation and primarily supports the frequency nadir and frequency arrest after the initial inertial phase [23].

Instantaneous reserve is delivered inherently by the rotating masses of the machines or synthetically by grid-forming converters. The full contracted contribution is associated with a design frequency gradient of 2 Hz/s, while smaller gradients activate a proportional share. Market-based procurement began on 22 January 2026 following the Federal Network Agency decision on the procurement concept.

The German framework distinguishes positive and negative directions and two availability qualities. Positive instantaneous reserve counteracts falling frequency, while negative instantaneous reserve counteracts rising frequency. The Basic product requires at least 30% annual availability, and the Premium product requires at least 90%. Availability is assessed in 15-minute intervals at unit or aggregated level.

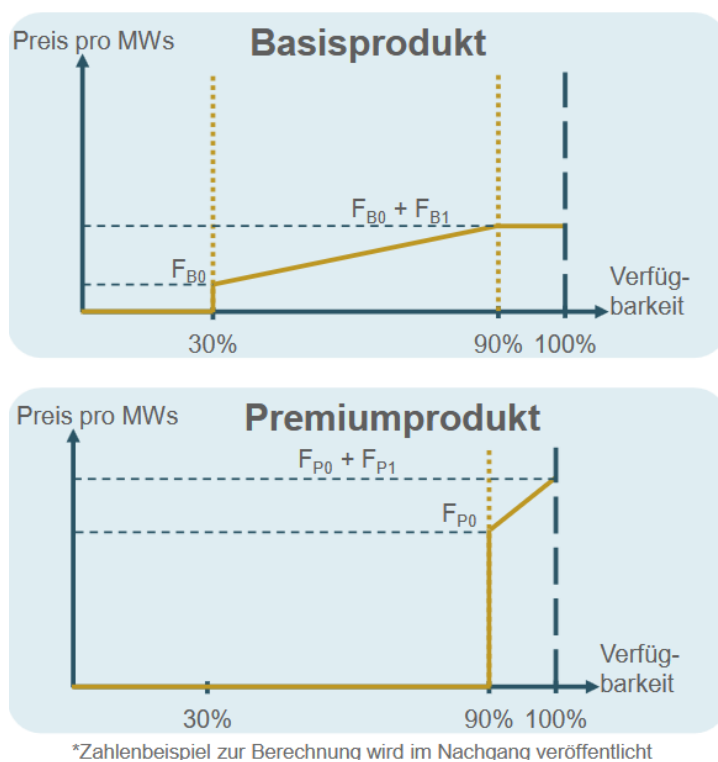
Converter-based units must maintain the required active-power headroom and, for storage, sufficient energy. Synchronous machines are assessed primarily through their synchronization status

and certified inertia contribution. The product is therefore based on continuous capability and availability rather than event-by-event energy delivery.



Disclaimer: Technologien rein indikativ und nicht abschließend

Figure 2-9: Indicative product and technology for instantaneous reserve in Germany



**Zahlenbeispiel zur Berechnung wird im Nachgang veröffentlicht*

Figure 2-10: Availability-dependent remuneration principle for the German Basic and Premium products

The four German TSOs procure instantaneous reserve within procurement regions that initially correspond to their control areas. The framework uses administratively determined fixed prices rather than a marginal auction-clearing price. Remuneration depends on the product, direction, procurement region and achieved availability during the annual settlement period.

For the Basic product, remuneration begins at 30% availability and increases up to 90%. For the Premium product, payment begins at 90% and increases to the maximum at 100%. Providers submit a certified instantaneous-reserve concept, assign eligible units in the relevant region and conclude a framework agreement through the prequalification portal.

Eligible resources include synchronous machines and grid-forming converter-based units. Depending on direction and operating point, suitable technologies may include BESS, wind and photovoltaic plants with grid-forming capability, flexible loads and synchronous machines operating as generators or synchronous condensers. Grid-following converters are not eligible for this kind of instantaneous reserve because they do not inherently establish the voltage angle and frequency response required for this product.

Relevance for the TwinEU FFR concept

The German case demonstrates that inertia-related products and FFR should be developed as complementary services. Instantaneous reserve limits the initial RoCoF, whereas threshold-based FFR acts later to improve the nadir and support arrest. A future Continental European framework may require both services, but their technical definitions, units of procurement, provider technologies and verification methods must remain clearly separated and complementary coordinated in the synergy of the frequency stability of the power system.

3 Regulatory-technical basis

This chapter assesses the European and Slovenian regulatory and technical framework relevant to the proposed Fast Frequency Response (FFR) service. It identifies the existing legal provisions that can support the development of FFR, clarifies where FFR is not yet explicitly recognized, and defines the principal regulatory adaptations required before operational and market implementation.

The analysis distinguishes between directly applicable and currently binding European legislation, operational agreements and implementation guidance, and ACER amendment proposals that were not yet adopted as binding Union law as of July 2026. This chapter is a technical-regulatory assessment and should not be interpreted as a formal legal opinion.

Core regulatory finding: FFR is not currently defined as a harmonized European reserve product. The most defensible initial classification is a dedicated frequency-related ancillary service based on reserved, prequalified and verifiable active-power capability. It should complement the primary processes in FSM and its market-based FCR, LFSM and System-defence measures without being treated as equivalent to any of them.

3.1 System operation guidelines (SOGL)

Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation (SOGL) is the principal European legal basis for operational security, frequency quality, load-frequency control and reserves. It defines the system states, frequency-quality parameters, the frequency containment process (FCP), the frequency restoration process (FRP), etc. [24].

FFR is not explicitly named or defined in the SOGL. The Regulation harmonizes FCR, FRR and RR, but does not establish a separate sub-second active-power reserve activated outside the normal FCR range. The proposed FFR service must therefore be introduced as a complementary national or control-area product while remaining consistent with the European frequency-control architecture.

Several SOGL provisions provide the principal technical baseline for such development:

- Article 18 defines the normal, alert, emergency, blackout and restoration states.
- Article 118 requires the synchronous-area operational agreement to specify common load-frequency-control and reserve arrangements.
- Article 127 and Annex III establish the frequency-quality defining parameters for each synchronous area.
- Article 142 defines the control objective of the FCP as stabilisation of system frequency through FCR.
- Articles 153 and 154 and Annex V establish FCR dimensioning and activation properties, including the Continental Europe full-activation deviation and time.

These provisions do not create FFR directly, but they define the boundaries within which a new FFR product must operate. In particular, FFR should not be presented as a replacement for FCR or as a modification of the European FCR obligation. It is a faster supplementary response intended for severe frequency excursions for which conventional FCR delivery may be too slow to secure an acceptable nadir or arrest frequency.

3.1.1 Electric power system states

The SOGL classifies a transmission system as being in the normal, alert, emergency, blackout or restoration state. This classification is based on several criteria, including steady-state frequency deviation and its duration, voltage and power-flow limits, reserve availability, operational-security violations and activation of measures from the system defence plan. A momentary crossing of a single frequency value does not, by itself, determine the legal system state.

3.1.1.1 Tolerable frequency nadir

For Continental Europe, Annex III establishes a standard frequency range of ± 50 mHz, a maximum steady-state frequency deviation of ± 200 mHz and a maximum instantaneous frequency deviation of ± 800 mHz. These values provide the main regulatory anchors for the proposed FFR activation characteristic.

Table 3-1: Frequency range parameters in SOGL relevant to the proposed FFR activation range

Reference level	Continental Europe value	Relevance to the proposed FFR concept
Standard frequency range	49.95–50.05 Hz	Routine frequency-quality range. FFR remains inactive.
FCR full-activation deviation / maximum steady-state deviation	± 200 mHz (49.8/50.2 Hz)	Proposed start of FFR activation. This separates FFR from the main FCR activation range.
Maximum instantaneous frequency deviation	± 800 mHz (49.2/50.8 Hz)	Proposed point of full FFR activation and outer reference for the intended static characteristic.

For example, consider the power system states (Article 18 of SOGL):

➤ Normal state	
➤ Alert state	
➤ Emergency state	
➤ Blackout state	
➤ Restoration state	

	CE
standard frequency range	± 50 mHz
maximum instantaneous frequency deviation	800 mHz
maximum steady-state frequency deviation	200 mHz
time to recover frequency	not used
frequency recovery range	not used
time to restore frequency	15 minutes
frequency restoration range	not used
alert state trigger time	5 minutes

Figure 3-1: Frequency nadirs in different power states of the Synchronous area of Continental Europe

The proposed FFR activation start at an absolute frequency deviation of 200 mHz is justified by two linked considerations. First, 200 mHz is the SOGL maximum steady-state frequency deviation for Continental Europe. Second, it is the FCR full-activation frequency deviation. Article 154 requires FCR activation to begin as soon as possible; for a deviation of at least 200 mHz, at least 50% of the full FCR capacity must be delivered within 15 s and 100% within 30 s. Below 200 mHz, the activated FCR capacity is at least proportional.

Keeping FFR inactive within ± 200 mHz avoids introducing a second procured product into the frequency range in which FCR is routinely active. This reduces direct product overlap and limits the risk that FFR procurement would reduce FCR provider's participation and/or market liquidity. It also avoids an immediate need to redesign the harmonized FCR process, including FCR dimensioning, prequalification, procurement, settlement and cross-border coordination.

However, the separation with the primary process of frequency containment is not absolute. The primary reserve in LFSM-U and/or LFSM-O becomes active at ± 200 mHz and beyond ⁴, and FFR activation at the boundary will therefore occur in parallel with these responses. The contractual and technical framework must consequently ensure that FFR capacity is additional or explicitly allocated, that the same active-power capability is not double counted or double remunerated, and that the combined control response remains stable.

Full FFR activation at ± 800 mHz aligns the service with the maximum instantaneous frequency deviation defined for Continental Europe. The values 49.2 Hz and 50.8 Hz should be interpreted as outer system-security reference levels. The full FFR response should be available no later than these limits because any further excursion lies outside the expected Continental Europe instantaneous frequency envelope and may approach or trigger system-defence measures. At 1000 mHz downwards frequency deviation the UFLS begins.

3.1.2 Continental Europe Synchronous Area Framework Agreement

The Continental Europe Synchronous Area Framework Agreement (SAFA) develops the synchronous-area operational agreement required by Article 118 of the SO GL and has applied since 14 April 2019. Its policies govern, among other matters, load-frequency control and reserves, emergency and restoration, data exchange, scheduling, accounting and settlement [25].

SAFA does not currently define a harmonized FFR product for Continental Europe. A Slovenian FFR service would therefore initially remain a control-area-specific arrangement and would need to be coordinated with SAFA rules on FCR, frequency-quality evaluation, system-state management and cross-border operational security.

During the development phase, limiting procurement and responsibility to a single control area is a reasonable approach. Exchange or sharing of FFR between control areas should not be introduced before the technical product, activation interactions, measurement rules, liability and settlement consequences have been jointly assessed. This restriction is particularly important because the service is locally activated from measured frequency but can have synchronous-area-wide effects.

Any later cross-border expansion would require coordinated amendments or additional arrangements addressing common product definitions, equivalent prequalification, locational constraints, cross-border capacity, settlement, activation verification and the allocation of operational responsibility. Until such coordination exists, the national TSO should remain responsible for dimensioning, procurement and verification within its control area.

These aspects are further analysed in the continuation of this deliverable.

⁴ For the specific frequency range see RfG and SOGL.

3.2 Requirement for Generators

Commission Regulation (EU) 2016/631 [26] establishing a network code on requirements for grid connection of generators (RfG) defines mandatory connection capabilities for power-generating modules. ACER Recommendation 03-2023 [27] contains a reasoned proposal for an amended RfG and is often referred to informally as “RfG 2.0”. At the cut-off date, it remained an amendment proposal submitted to the European Commission for public consultation rather than adopted binding legislation.

Neither the current RfG nor the ACER amendment proposal creates an FFR ancillary-service product. They nevertheless provide an important technical basis because they define frequency perturbation withstand capability, frequency-sensitive modes, LFSM-O and LFSM-U, active-power response performance, electricity-storage, EV V2G capabilities and compliance testing, and most importantly grid-forming capabilities.

In the light of RfG and the FFR concept, a connection requirement and an ancillary service must remain conceptually separate. RfG capability establishes what an applicable unit must technically be able to do as a condition of connection. FFR would require additional operational and commercial conditions, including reserved active-power headroom, energy availability, continuous service availability, prequalification, measurement at the point of common coupling, verification, remuneration and non-delivery consequences.

The same distinction applies to setpoint and delivered active power. An internal controller may calculate a frequency-dependent active-power setpoint very quickly, but system support is provided only when active power is physically delivered at the point of common coupling. FFR timing and compliance should therefore be assessed from the crossing of the activation threshold to the measurable active-power response and full delivery, not only to internal setpoint generation. For details see Chapter 4.3.3.6.

3.3 Network Code on Emergency and Restoration

Commission Regulation (EU) 2017/2196 [28] establishing a network code on electricity emergency and restoration (NC ER) governs emergency, blackout and restoration states, system defence plans, restoration plans and related testing. FFR is not explicitly named in the Regulation.

The NC ER is nevertheless highly relevant because the proposed FFR service is primarily intended to improve frequency behaviour during severe disturbances, system separations and islanded operation. Article 11 requires the system defence plan to include automatic underfrequency and overfrequency schemes, frequency-deviation management, active-power assistance and other coordinated measures. Article 15 requires LFSM-U to be activated before automatic low-frequency demand disconnection where the RoCoF allows it and requires storage operating as load to switch to generation or disconnect according to TSO-defined thresholds and time limits.

FFR should not automatically be classified as a defence service under the NC ER. It would acquire that role only where it is explicitly included in the system defence plan or where a provider assumes a legal or contractual obligation to contribute to one or more defence-plan measures. Otherwise, FFR remains a frequency-related ancillary service that must be coordinated with, but is legally distinct from, defence and restoration services.

The NC ER supports the proposed emphasis on geo-electrical dispersion. The location, capacity and availability of FFR providers should be assessed against possible system-split and islanding

configurations and coordinated with defence and restoration plans. This reduces the risk that a large contracted capacity becomes unavailable or ineffective after network separation.

The Regulation also establishes a strict testing principle. Article 43 requires test plans for relevant equipment and capabilities and states that tests must not endanger the operational security of the transmission system or the interconnected system and must minimize the impact on system users. This supports simulation-based system validation, controller testing, signal-injection testing and hardware-in-the-loop assessment rather than deliberately creating a severe system-wide frequency disturbance.

3.4 Network Code on Demand Connection

Commission Regulation (EU) 2016/1388 [29] establishing a Network Code on Demand Connection (NC DC) provides a legal and technical precedent for frequency-responsive demand. The ACER proposal for an amended NC DC [30] extends the treatment of different types of demand such as P2X technologies but does not establish a harmonized FFR product.

However, their timing and measurement requirements are materially less demanding than the TwinEU FFR proposal.

3.5 Clean energy package (CEP) of regulations and directives

The Clean Energy Package provides the main legal framework for classifying and procuring ancillary and balancing services. The most relevant instruments are Directive (EU) 2019/944 [31], Regulation (EU) 2019/943 [32], Regulation (EU) 2019/941 [33] on risk preparedness.

Directive (EU) 2019/944 defines an ancillary service as a service necessary for the operation of a transmission or distribution system, including balancing and non-frequency ancillary services. Its definition of non-frequency ancillary services covers voltage control, reactive current, inertia for local grid stability, short-circuit current, black start and island-operation capability. Since the proposed FFR service provides active-power response to a frequency deviation, it should not be classified as a non-frequency ancillary service.

Proposed classification: FFR should be classified as a frequency-related ancillary service. Commercially, it should initially be procured as an availability or reserved-capacity product with verified active-power delivery. If it is later integrated into the System Operation and Electricity Balancing framework, it could be developed as a specific balancing-capacity product, but this would require explicit national terms and conditions and regulatory approval.

The market-design principles in Directive (EU) 2019/944 and Regulation (EU) 2019/943 require transparent, non-discriminatory, technology-neutral and market-based procurement, with participation open to qualified generation, storage, demand response and aggregation. FFR eligibility should therefore be based on demonstrated performance rather than technology, while allowing additional locational and operational requirements where justified by system security and stability.

A contract-based product can comply with these principles if procurement is competitive, transparent and non-discriminatory. During the development phase, annual or multi-year contracts may be justified by the small number of qualified providers, the need for investment certainly and limited market liquidity. Direct bilateral procurement without competition would require a clear legal basis, objective justification and consistency with national and Union procurement and market rules.

The interaction with FCR is a central regulatory issue. FCR is a harmonized synchronous-area reserve product, while FFR is proposed as a local control-area product. FFR procurement should not withdraw material capacity from FCR, weaken FCR competition or create double remuneration. However, in the emerging era of very fast and precise technologies, an FFR vs. FCR threshold adaptation and further coordination will be certainly needed.

Regulation (EU) 2019/941 is relevant because FFR may contribute to resilience during electricity-crisis scenarios. It does not create the service, but it supports coordination between preventive, operational and crisis-preparedness measures. FFR should be recognized in risk-preparedness analysis where its availability materially changes the consequences of system separation, low inertia or major active-power imbalance.

3.5.1 Electricity supply act of Slovenia (*Zakon o oskrbi z električno energijo*)

The Slovenian Electricity Supply Act (or *Zakon o oskrbi z električno energijo* - ZOE) [34] represents the national law of Slovenia transferring the objectives of the Directive 2019/944/EU and provides the national enabling basis for system operation and ancillary services. Article 136 requires system operating instructions to regulate, among other matters, secure system operation, the provision of system services, crisis-state procedures, connection conditions, technical coordination and data exchange. This provision is sufficiently broad to support the future introduction of FFR, but the service is not explicitly defined in the Act.

The process of FFR full implementation is a regulatory challenge but also an opportunity for detailed future work. National implementation would require coordinated amendments to legislation, including national system operating guidelines, market rules, connection and prequalification procedures, contractual documentation and other technical guidelines for performance verification, either by tests and/or simulations.

The regulatory development should be staged. An initial national pilot can establish technical evidence, provider capability and operational experience. A permanent service should follow only after the regulator, TSO and market participants have agreed the product definition, need-assessment methodology, procurement model and interaction with existing European and national frequency-control processes. The activities within this task are the first wave of such development.

3.6 Network Code on Demand Response proposal

ACER Recommendation 01-2025 [35] contains a reasoned proposal for establishing a European network code on demand response. At the cut-off date, the proposal was not binding Union law and did not create an FFR product. Its relevance lies in the future market and operational architecture for distributed flexibility, energy storage, aggregation and TSO–DSO coordination.

The proposal addresses product prequalification, qualification of service providers, data exchange, verification, aggregation and coordinated use of distributed resources. These mechanisms could later support FFR participation by resources connected below the transmission level, provided that the technical performance of the aggregated response can be measured and guaranteed at the relevant connection or aggregation boundary.

For the initial FFR implementation, transmission-connected providers remain the more pragmatic scope because the TSO can directly observe, prequalify and verify the response and can assess its locational effect in the transmission system. The Demand Response Network Code proposal should be

monitored as a potential enabling framework for a later expansion of eligibility, not as a current legal basis for assuming unrestricted participation of distributed resources.

Regulatory conclusion: No harmonized FFR product is defined in the European framework. Existing rules provide enabling concepts but not a complete service definition. Namely, the current framework does not prevent the development of FFR, but it does not provide a ready-to-use legal product.

Implementation requires a deliberate regulatory design that preserves and/or adapts the integrity of the frequency ancillary services, aligns with system-defence and restoration processes, enables technology-neutral participation, and establishes transparent national rules for procurement and verification. This regulatory gap is both a challenge and a clear opportunity for future work within the wider Continental Europe frequency-stability framework.

This deliverable offers a structured multidisciplinary analysis for future European and national regulatory development of FFR, and in particular provides the technical evidence and product-design basis for the necessary adaptation of regulations, national law and operational guidelines.

4 The FFR concept

This is the main core chapter of the FFR concept development. It presents the proposed concept of Fast Frequency Response (FFR) for the Slovenian control area which is scalable to each the control area of the Synchronous Area of Continental Europe. It defines the algorithm and product, its activation principles and dynamic performance, and then evaluates the influence of the main technical parameters through sensitivity analysis. The chapter further addresses FFR capacity planning, unit-level requirements, market and procurement aspects, and concludes with a consolidated summary of the proposed technical and system criteria.

4.1 The definition of the FFR

FFR is defined as a very fast, frequency deviation-dependent active-power response intended to support the electric power system during the initial period following a significant frequency disturbance. The service is designed to improve the frequency nadir, support frequency arrest and bridge the period between the initial inertial response and the effective activation of slower frequency-control processes.

The proposed FFR concept combines a static frequency–power characteristic with clearly defined dynamic response requirements. The following subsection presents the product formulation, visual representation and activation algorithm used to determine the requested and delivered FFR response.

4.1.1 Product formulation with visualization and algorithm for service activation

This formulation is intended for the analysis of **Fast Frequency Reserve (FFR)** in the first seconds after a disturbance, with explicit focus on the interaction between:

- the **static** P - f characteristic, which defines the requested FFR power as a function of frequency deviation, and
- the **dynamic** realization of that request, which is limited by activation delay and finite ramping capability.

To isolate the short-term contribution of FFR, the analysis deliberately neglects:

- the damping D ,
- primary reserve activation, either in FSM or LFSM, due to the slower activation and
- secondary and tertiary control actions, due to the different nature and activation in a different phase.

Accordingly, the model is intended for **early-transient frequency-nadir assessment**, not for long-term frequency restoration.

The original P - t characteristic from the frequency bump test remains relevant as a **compliance description** of the resource capability. However, for actual system-frequency simulations, the correct formulation is not an exogenous $P(t)$, but a **closed-loop model** in which the FFR output depends on the evolving frequency deviation.

Notation and basic definitions

Let

$$f_n = f_0 = 50 \text{ Hz}$$

denote the nominal system frequency, and let

$$\Delta f(t) = f(t) - f_0$$

denote the instantaneous frequency deviation.

Further, let

$$P_{\text{ref}}$$

be the reference active power of the FFR-providing unit or equivalent aggregated resource, and

$$P_{\text{op}}(t) = P_{\text{ref}} + P_{\text{FFR}}(t)$$

the actual operating active power in the control area of interest. The power the right-hand-side is normalized power [pu] on the systems power base $S_{\text{sys,base}}$ – a choice directly impacting the representation of the system inertia (see below).

The static FFR thresholds are defined as

$$\Delta f_1 = 0.2 \text{ Hz}, \Delta f_2 = 0.8 \text{ Hz}.$$

Thus:

- $|\Delta f| \leq \Delta f_1$: deadband, no FFR requested,
- $\Delta f_1 < |\Delta f| < \Delta f_2$: proportional activation,
- $|\Delta f| \geq \Delta f_2$: full activation.

The available FFR capacity is

$$P_{\text{FFR}}^{\text{max}} > 0.$$

The disturbance is modelled as a constant power imbalance

$$\Delta P_{\text{dist}} > 0,$$

interpreted here as a generation deficit or net power shortfall causing under-frequency.

The instant at which the activation threshold is first reached is denoted by

$$t_{|\Delta f_1|} \equiv \inf\{t \geq 0: |\Delta f(t)| = \Delta f_1\} = t_{|\Delta f(t \geq 0)| = \Delta f_1}$$

The dynamic implementation parameters are:

- t_1 : delay between reaching $|\Delta f| = \Delta f_1$ and the actual start of FFR delivery,
- t_2 : time from reaching $|\Delta f| = \Delta f_1$ to full activation in the bump test,
- t_3 : full-activation holding time in the bump test,
- T_{down} : ramp-down time in the bump test.

In the **closed-loop** analysis below, the nadir is mainly governed by t_1 , t_2 , and the static P - f command characteristic. The parameters t_3 and T_{down} are important for compliance testing and energy delivery, but not for the initial frequency nadir under the present assumptions.

For compactness, define the clipping operator as

$$\text{clip}(x, a, b) = \min\{\max\{x, a\}, b\}.$$

Static P-f characteristic as the commanded response

The static characteristic should be interpreted as the **commanded FFR power**, not yet as the realised output.

Define the normalized activation factor

$$\alpha_{\text{FFR}}(\Delta f) = \text{clip}\left(\frac{|\Delta f| - \Delta f_1}{\Delta f_2 - \Delta f_1}, 0, 1\right).$$

Then the commanded FFR power is

$$P_{\text{FFR}}^{\text{cmd}}(\Delta f) = -\text{sgn}(\Delta f) P_{\text{FFR}}^{\text{max}} \alpha_{\text{FFR}}(\Delta f).$$

This compact expression reproduces the full symmetric static characteristic:

- for under-frequency, $\Delta f < 0$ Hz, the sign is positive and active power is injected,
- for over-frequency, $\Delta f > 0$ Hz, the sign is negative and active power is withdrawn,
- within the deadband, $\alpha_{\text{FFR}} = 0$, hence no FFR is requested.

Equivalently, in explicit piecewise form,

$$P_{\text{FFR}}^{\text{cmd}}(\Delta f) = \begin{cases} -P_{\text{FFR}}^{\text{max}}, & \Delta f \leq -\Delta f_2, \\ P_{\text{FFR}}^{\text{max}} \frac{-\Delta f - \Delta f_1}{\Delta f_2 - \Delta f_1}, & -\Delta f_2 < \Delta f < -\Delta f_1, \\ 0, & |\Delta f| \leq \Delta f_1, \\ -P_{\text{FFR}}^{\text{max}} \frac{\Delta f - \Delta f_1}{\Delta f_2 - \Delta f_1}, & \Delta f_1 < \Delta f < \Delta f_2, \\ -P_{\text{FFR}}^{\text{max}}, & \Delta f \geq \Delta f_2. \end{cases}$$

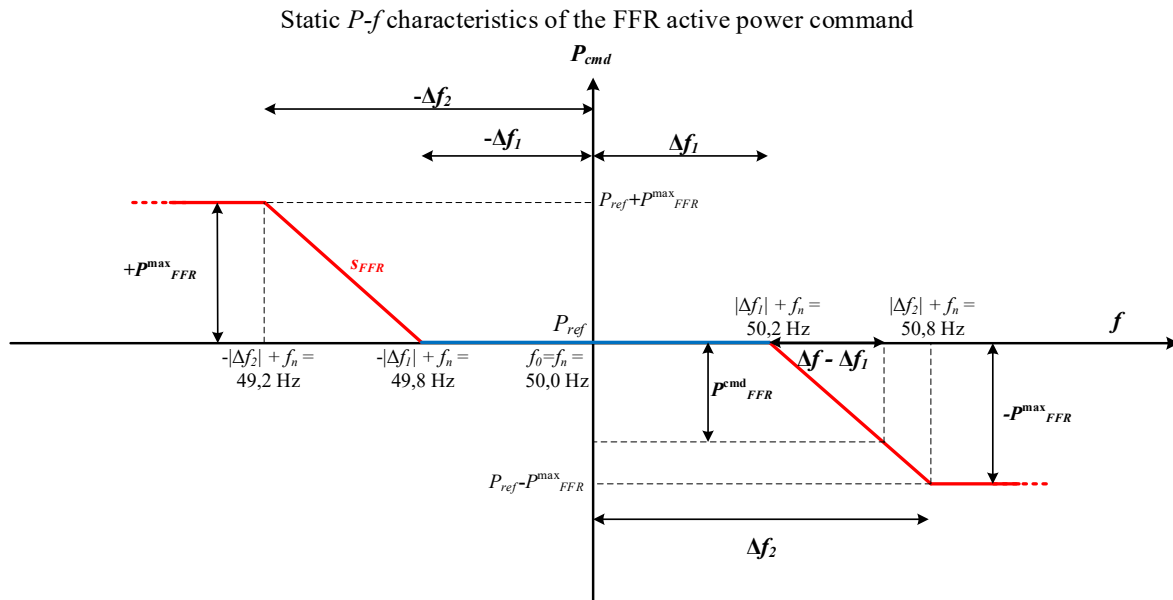


Figure 4-1 – Static P-f characteristic of the FFR active power command

The corresponding operating power is

$$P_{\text{Op}}(t) = P_{\text{ref}} + P_{\text{FFR}}(t),$$

where $P_{FFR}(t)$ is the **realised or active** power, not necessarily equal to the command.

Static characteristic plot is graphically represented in Figure 4-1.

Dynamic P-t realization of the commanded FFR power

The static characteristic tells us **how much** FFR should be delivered for a given frequency deviation. It does not tell us **how fast** the resource can realise that request.

Figure 4-2 presents the dynamic P-t characteristic of the FFR response for a frequency bump test with a step-wise frequency deviation of $|\Delta f| = 800$ mHz. The figure illustrates the required time behaviour of the active-power response after the frequency deviation exceeds the activation threshold of $|\Delta f| = 200$ mHz and how fast is FFR capable to reach its maximum capacity at $|\Delta f| = 800$ mHz.

P-t characteristics of the FFR frequency bump test (in case of a step-wise $|\Delta f| = 800$ mHz)

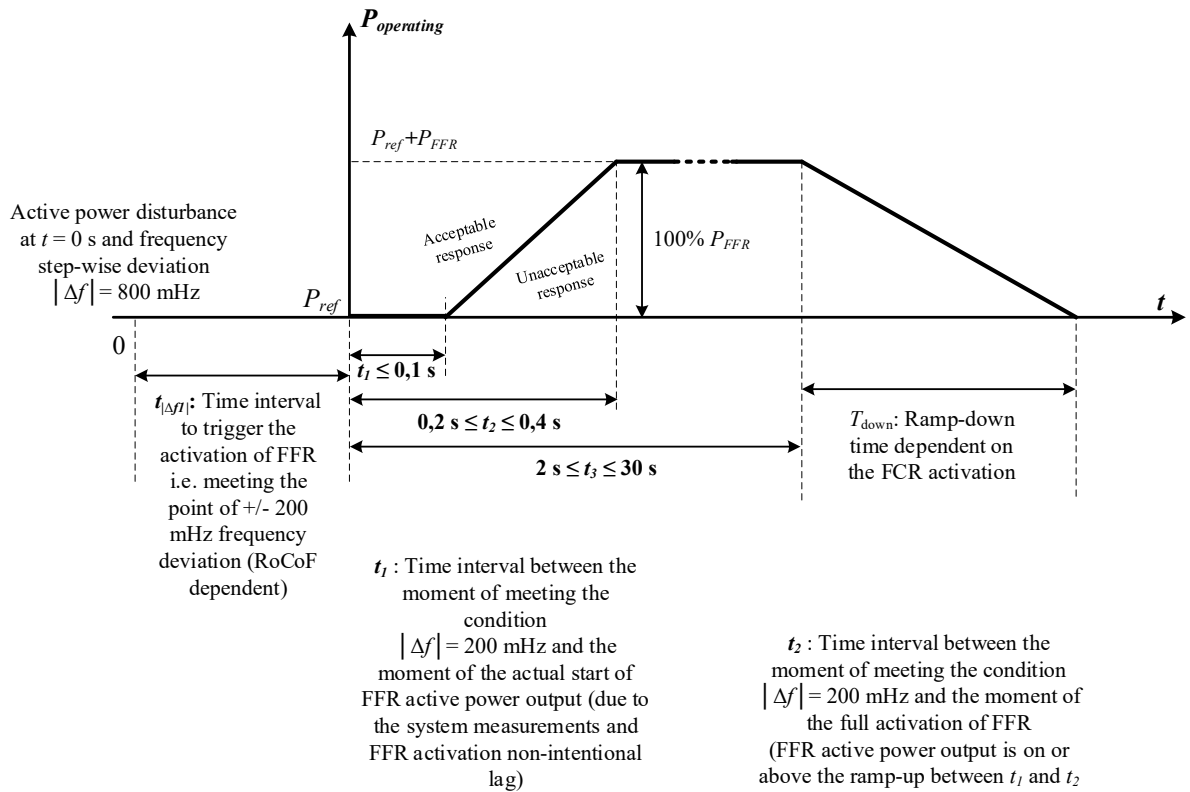


Figure 4-2 - Dynamic P-t characteristic of the FFR response for a frequency bump test of 800 mHz

After the disturbance occurs at $t = 0$ s, the frequency deviation develops until the activation condition is met. The time needed to reach the activation threshold is denoted as $t_{|\Delta f_1|}$ and depends on the initial RoCoF. Once the threshold is reached, the FFR response is not necessarily instantaneous. The parameter t_1 represents the delay between meeting the activation condition and the actual start of active-power delivery. According to the illustrated requirement, this delay should not exceed 0.1 s.

The FFR output then ramps up from zero to full activation. The parameter t_2 represents the time between reaching the activation threshold and reaching full FFR activation. For the illustrated frequency bump test, full activation should be reached within the interval:

$$0.2 \text{ s} \leq t_2 \leq 0.4 \text{ s}.$$

During the ramp-up interval between t_1 and t_2 , the response is acceptable if the delivered active power follows or exceeds the required ramp trajectory. Responses below the required trajectory are considered insufficient.

After full activation is reached, the FFR contribution remains at 100% of the contracted FFR capacity for a defined holding period. The duration of this full-activation phase is represented by t_3 , with the indicative range:

$$2 \text{ s} \leq t_3 \leq 30 \text{ s}.$$

The final phase is the ramp-down of the FFR response. This deactivation should be coordinated with the activation of slower frequency-control mechanisms, primarily with primary droop-control responses in FSM (for example FCR) and/or LFSM. The ramp-down time T_{down} is therefore not a fixed intrinsic FFR parameter only, but depends on the wider frequency-control coordination. An indicative limitation to a 30 s duration is preferable.

Furthermore, to describe the implementation dynamics, we define a delayed activation gate

$$g(t) = u(t - t_{|\Delta f_1|} - t_1),$$

where $u(\cdot)$ is the Heaviside step function.

The delayed effective command is then

$$P_{\text{FFR}}^{\text{cmd,d}}(t) = g(t) P_{\text{FFR}}^{\text{cmd}}(\Delta f(t)).$$

This means:

- before the threshold is reached, no FFR is requested,
- after the threshold is reached, the request is still blocked during the delay t_1 ,
- once the delay expires, the resource starts tracking the frequency-dependent command.

A compact closed-loop dynamic model for the realised FFR power is

$$\dot{P}_{\text{FFR}}(t) = \text{clip}(K_t [P_{\text{FFR}}^{\text{cmd,d}}(t) - P_{\text{FFR}}(t)], -R_{\downarrow}, R_{\uparrow}),$$

where:

- $K_t > 0$ is a tracking gain,
- $R_{\uparrow}$ is the maximum upward ramp rate,
- $R_{\downarrow}$ is the maximum downward ramp rate.

For a full-scale step request in the bump test, the parameter t_2 is connected to the upward ramp rate through

$$R_{\uparrow} \approx \frac{P_{\text{FFR}}^{\text{max}}}{t_2 - t_1}.$$

This relation is crucial: it embeds the P - t capability into the closed-loop formulation. In other words:

- the **static** P - f law generates the command,
- the **dynamic** P - t capability limits how quickly that command can be realised.

The bump test therefore remains the correct way to parameterize t_1 , t_2 , and the ramping capability, but not the correct way to impose the actual FFR output in a closed-loop frequency simulation.

4.2 Sensitivity analysis

For integral execution of the sensitivity analysis, a strict formulation of the closed-loop testing model is necessary. Such model is graphically shown at the following figure:

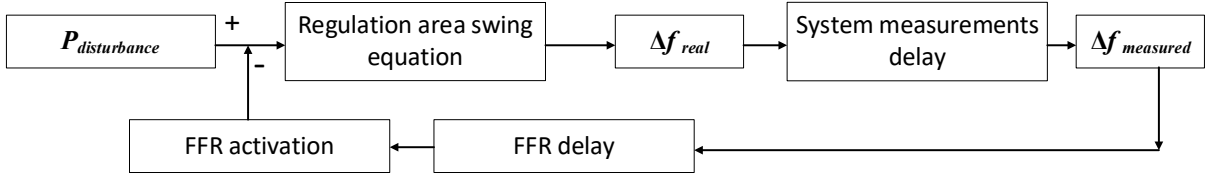


Figure 4-3 - Simplified FFR block diagram

Under the present simplifications, the aggregate frequency dynamics are described by

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -\Delta P_{\text{dist}} + P_{\text{FFR}}(t),$$

Where $H = H_{\text{sys}}$ [s] is the equivalent inertia coefficient of the system in the control area of interest:

$$\begin{aligned} H = H_{\text{sys}} &= \frac{\sum_{i=1}^k H_{i,\text{conv}} S_{i,\text{conv}} + \sum_{j=1}^k H_{j,\text{synth}} S_{j,\text{synth}}}{\sum_{i=1}^k S_{i,\text{conv}} + \sum_{j=1}^k S_{j,\text{synth}}} = \\ &= \frac{\sum_{i=1}^k H_{i,\text{conv}} S_{i,\text{conv}} + \sum_{j=1}^k H_{j,\text{synth}} S_{j,\text{synth}}}{S_{\text{sys},\text{base}}} \end{aligned}$$

which includes the conventional inertia constants $H_{i,\text{conv}}$, and also synthetic inertia constants $H_{j,\text{synth}}$.

This means that:

- the disturbance ΔP_{dist} drives the frequency down,
- the static P - f characteristic creates a frequency-dependent FFR command,
- the realised FFR output follows that command with delay and ramp limitation,
- the resulting FFR power feeds back into the swing equation.

Before any FFR action takes place,

$$P_{\text{FFR}}(t) = 0,$$

and therefore

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -\Delta P_{\text{dist}}.$$

Hence the initial RoCoF is

$$\text{RoCoF}_0 = \dot{f}(0^+) = -\frac{f_0 \Delta P_{\text{dist}}}{2H}.$$

Since damping and FCR are neglected, the frequency decline before activation is strictly linear, and the threshold-reaching time is

$$t_{|\Delta f_1|} = \frac{\Delta f_1}{|\text{RoCoF}_0|}.$$

For $\Delta f_1 = 0.2$ Hz,

$$t_{|\Delta f_1|} = \frac{0.2 \text{ Hz}}{|\text{RoCoF}_0|}.$$

This is one of the key relations in the sensitivity analysis, because it shows directly how fast the threshold is reached for a given initial RoCoF.

The analytical interpretations of the closed-loop model are as follows:

Ideal instantaneous realization as a reference case

The cleanest analytical interpretation is obtained by first considering the idealized limit

$$t_1 = 0 \text{ s}, R_{\uparrow} \rightarrow \infty,$$

so that

$$P_{\text{FFR}}(t) = P_{\text{FFR}}^{\text{cmd}}(\Delta f(t)).$$

This ideal case is not the physical implementation, but it is the correct analytical reference. It shows the intrinsic feedback structure of the static P - f law.

Regime I: deadband

For

$$-\Delta f_1 \leq \Delta f \leq 0 \text{ Hz}$$

during an under-frequency event, no FFR is requested. Therefore,

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -\Delta P_{\text{dist}},$$

and the solution is

$$\Delta f(t) = \text{RoCoF}_0 t.$$

This linear decline continues until the threshold $-\Delta f_1$ is reached.

Regime II: proportional activation region

For

$$-\Delta f_2 < \Delta f < -\Delta f_1,$$

the static law is linear:

$$P_{\text{FFR}}^{\text{cmd}}(\Delta f) = P_{\text{FFR}}^{\text{max}} \frac{-\Delta f - \Delta f_1}{\Delta f_2 - \Delta f_1}.$$

Substituting this into the swing equation gives

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -\Delta P_{\text{dist}} + P_{\text{FFR}}^{\text{max}} \frac{-\Delta f - \Delta f_1}{\Delta f_2 - \Delta f_1}.$$

After rearrangement,

$$\dot{\Delta f}(t) + \frac{P_{\text{FFR}}^{\text{max}}}{\frac{2H}{f_0}(\Delta f_2 - \Delta f_1)} \Delta f(t) = -\frac{\Delta P_{\text{dist}}}{\frac{2H}{f_0}} - \frac{P_{\text{FFR}}^{\text{max}} \Delta f_1}{\frac{2H}{f_0}(\Delta f_2 - \Delta f_1)}.$$

This is a first-order linear differential equation. Its solution is

$$\Delta f(t) = \Delta f_{\text{eq}}^{\text{ideal}} + (\Delta f(t_a) - \Delta f_{\text{eq}}^{\text{ideal}}) \exp\left(-\frac{P_{\text{FFR}}^{\text{max}}}{\frac{2H}{f_0}(\Delta f_2 - \Delta f_1)}(t - t_a)\right),$$

where t_a is the entry time into the proportional zone and $\Delta f_{\text{eq}}^{\text{ideal}}$ is the equilibrium implied by the static law.

Ideal equilibrium frequency elaboration

The ideal equilibrium target represents the frequency at which the activated FFR power exactly compensates for the disturbance. At this point, the remaining active-power imbalance is zero and the frequency stops changing.

The target depends on the relationship between the disturbance size and the available FFR capacity. A smaller disturbance requires only partial FFR activation, while a disturbance equal to the full available FFR capacity requires full activation. If the disturbance exceeds the available FFR capacity, FFR alone cannot establish an equilibrium.

The term *ideal* indicates that the target is based on a simplified analytical representation. It does not include activation delay, ramp limitations, load damping, primary control or other system dynamics. It should therefore not be interpreted as the actual frequency nadir or as the desired long-term operating frequency.

Define the disturbance-to-FFR ratio

$$r = \frac{\Delta P_{\text{dist}}}{P_{\text{FFR}}^{\text{max}}}.$$

Then the ideal equilibrium in the proportional region is obtained by setting $\dot{\Delta f} = 0$, i.e.

$$P_{\text{FFR}}^{\text{cmd}}(\Delta f_{\text{eq}}^{\text{ideal}}) = \Delta P_{\text{dist}}.$$

This yields

$$\Delta f_{\text{eq}}^{\text{ideal}} = -\Delta f_1 - r(\Delta f_2 - \Delta f_1).$$

With $\Delta f_1 = 0.2$ Hz and $\Delta f_2 - \Delta f_1 = 0.6$ Hz,

$$\Delta f_{\text{eq}}^{\text{ideal}} = -(0.2 + 0.6r) \text{ Hz}.$$

This result is central, and it is closely related to SOGL (see chapter 3.1).

For the three sensitivity ratios:

- $r = 0.5 \Rightarrow \Delta f_{eq}^{ideal} = -0.5 \text{ Hz}$,
- $r = 1.0 \Rightarrow \Delta f_{eq}^{ideal} = -0.8 \text{ Hz}$,
- $r = 1.5 \Rightarrow$ no equilibrium exists inside the activation range.

This immediately explains the three regimes:

- $r < 1$: FFR is strong enough to balance the disturbance before full saturation,
- $r = 1$: equilibrium is reached exactly at full static activation,
- $r > 1$: even full FFR cannot balance the disturbance.

The graphical representation of the ideal equilibrium target is shown at the following figure:

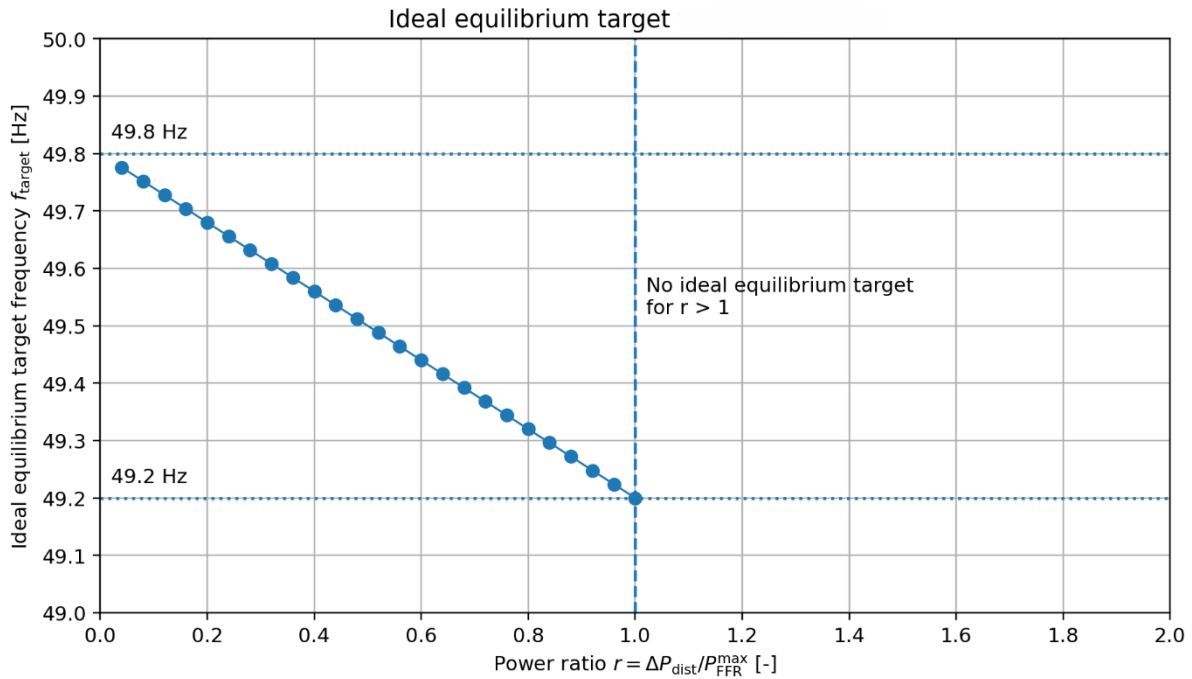


Figure 4-4 - Frequency deviation with and without FFR

Regime III: saturated FFR

If the frequency reaches

$$\Delta f \leq -\Delta f_2,$$

then the static command saturates at

$$P_{FFR}^{cmd} = P_{FFR}^{max}.$$

The swing equation becomes

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -(\Delta P_{dist} - P_{FFR}^{max}).$$

Thus:

- if $r < 1$, the slope becomes positive after saturation and frequency recovers,
- if $r = 1$, the slope becomes zero and frequency is arrested at the saturation boundary,
- if $r > 1$, the slope remains negative and frequency continues to decline.

For $r > 1$, the residual post-saturation slope is

$$\dot{f}_{\text{sat}} = -\frac{\Delta P_{\text{dist}} - P_{\text{FFR}}^{\text{max}}}{\frac{2H}{f_0}} = -|\text{RoCoF}_0| \left(1 - \frac{1}{r}\right).$$

This means that, under the inertia-plus-FFR-only model, **no timing optimization can produce arrest** if $r > 1$. In that regime, more FFR capacity is required, or slower control layers must intervene.

Details follow in the subchapters of the sensitivity analysis.

Why finite t_1 and t_2 worsen the nadir

The ideal formulation above is useful because it shows what the static characteristic would do under instantaneous realization. The real implementation differs because the realised power does not track the command immediately.

Define the tracking deficit

$$e_P(t) = P_{\text{FFR}}^{\text{cmd,d}}(t) - P_{\text{FFR}}(t).$$

Then the closed-loop swing equation may be rewritten as

$$\frac{2H}{f_0} \dot{\Delta f}(t) = -\Delta P_{\text{dist}} + P_{\text{FFR}}^{\text{cmd,d}}(t) - e_P(t).$$

Compared with the ideal case, the term $-e_P(t)$ is an additional negative contribution. In plain terms:

- the static law may already be asking for support,
- but the resource has not yet delivered the full requested power,
- therefore, the net accelerating power remains more negative,
- and the frequency falls deeper than in the ideal case.

This is exactly why t_1 and t_2 matter.

The effect of t_1 is especially direct: during the interval

$$t_{|\Delta f_1|} \leq t < t_{|\Delta f_1|} + t_1,$$

the resource is still inactive, so the frequency continues to decline approximately with the inertial slope RoCoF_0 . The additional loss accumulated during this pure delay is approximately

$$\Delta f_{\text{delay}} \approx |\text{RoCoF}_0| t_1.$$

The effect of t_2 is different. Once activation has started, the reserve is already responding, but a slower ramp means that the realised output remains below the commanded output for longer. Therefore, the integral of the tracking deficit $e_P(t)$ increases, which deepens the frequency minimum.

The important implication is this:

- in slow events, the proportional static law has time to shape the response, and the actual minimum remains close to the ideal equilibrium,
- in fast events, inertia carries the frequency below the ideal equilibrium before the realised FFR catches up.

That is why the same static characteristic can perform well at -1 Hz/s and much worse at -5 Hz/s, even if $P_{\text{FFR}}^{\text{max}}$ is unchanged.

Role of the original bump-test P - t characteristic

The bump test still has a clear role in the formulation. It does not replace the static P - f law but parameterizes the dynamic realization of that law.

Specifically:

- t_1 represents the activation delay,
- t_2 determines the maximum ramping capability,
- t_3 and T_{down} characterize the full activation hold and release in compliance tests.

For actual closed-loop frequency simulations, the early nadir is governed by the combination of:

1. the threshold logic from the static law,
2. the frequency-dependent command,
3. the delayed and rate-limited realization of that command.

So the correct modelling hierarchy is:

static $P - f \Rightarrow P_{\text{FFR}}^{\text{cmd}} \Rightarrow$ dynamic realization via $t_1, t_2 \Rightarrow P_{\text{FFR}}(t) \Rightarrow$ closed-loop model dynamics.

We continue to the elaboration of the multi-scenario sensitivity analysis understanding the specifications of the model. The sensitivity study is restricted to **under-frequency events**, because the over-frequency side is symmetric.

4.2.1 Parameters of interest and an example of the sensitivity analysis

The parameter ranges are:

$$\begin{aligned} \text{RoCoF}_0 &\in \{-0.5, -1, -2, -4, -5\} \text{ Hz/s}, \\ r &= \frac{\Delta P_{\text{dist}}}{P_{\text{FFR}}^{\text{max}}} \in \{0.5, 1.0, 1.5\}, \\ t_1 &\in \{0, 0.05, 0.10\} \text{ s}, \\ t_2 &\in \{0.2, 0.3, 0.4\} \text{ s}. \end{aligned}$$

The base case is

$$\text{RoCoF}_0 = -2 \frac{\text{Hz}}{\text{s}}, r = 1.0, t_1 = 0.05 \text{ s}, t_2 = 0.30 \text{ s}.$$

In the numerical study, the model is normalized so that the same RoCoF_0 and r are preserved while avoiding unnecessary dependence on absolute base power. This does not change the frequency trajectories in normalized form, only the scaling of the power axis.

An example is shown in Figure 4-5. It shows the influence of the initial RoCoF on the closed-loop frequency response for the reference case in which the available FFR capacity equals the disturbance size.

A higher absolute RoCoF results in a faster frequency decline and reduces the time available for the FFR response to develop. Although the activation threshold is reached earlier, the frequency continues to decrease during the activation delay and ramp-up period.

For lower RoCoF values, the FFR response develops sufficiently quickly and the frequency approaches the ideal equilibrium target. For higher RoCoF values, the frequency falls below this target before the full FFR response is delivered, resulting in a lower arrest frequency.

The results demonstrate that sufficient FFR capacity alone does not guarantee an acceptable frequency response. The final outcome also depends strongly on the initial RoCoF, activation delay and FFR ramp rate.

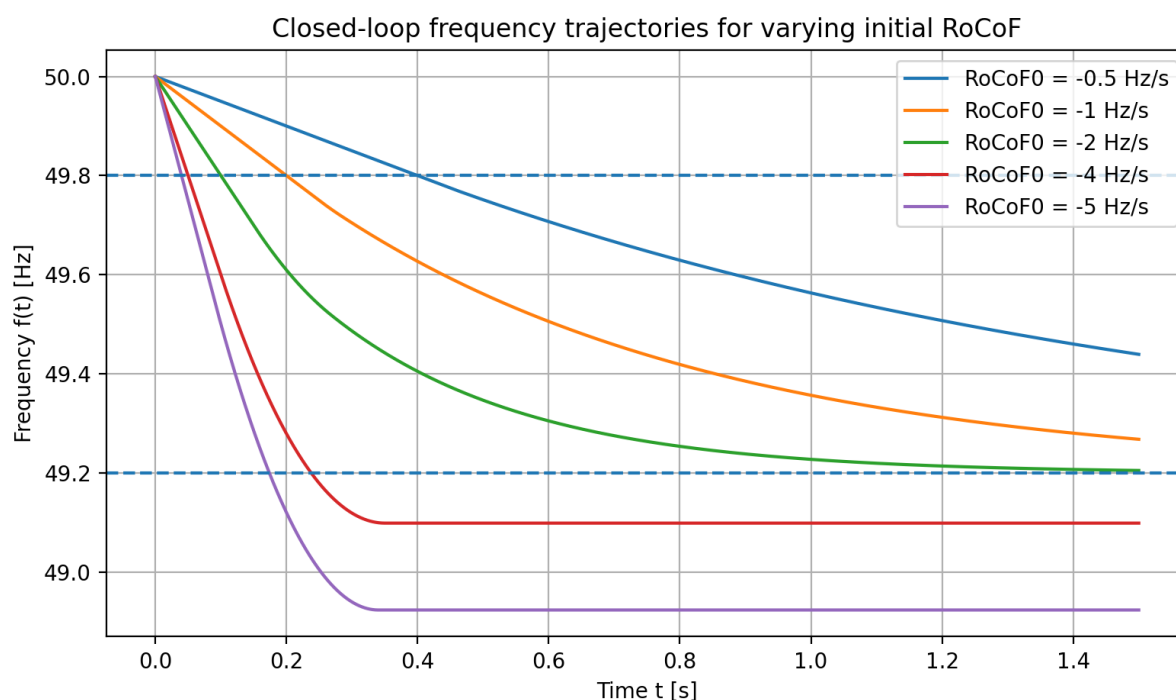


Figure 4-5 – Frequency trajectories for different initial RoCoF values

4.2.2 Sensitivity to the initial RoCoF

The sensitivity analysis evaluates the influence of the initial RoCoF while keeping the disturbance-to-FFR ratio equal to one. Consequently, the maximum available FFR capacity is sufficient to compensate for the disturbance, provided that the response is delivered quickly enough.

The results show that the initial RoCoF has a decisive influence on the minimum frequency and the final arrest frequency. A higher absolute RoCoF causes a faster frequency decline and increases the frequency loss accumulated during the FFR activation delay and ramp-up period. Although the activation threshold is reached earlier, less time remains for the FFR response to develop before the frequency reaches critical values.

For the fastest response setting, with no activation delay and full activation within 200 ms, all analysed trajectories remain controlled and converge towards the ideal equilibrium target of 49.2 Hz. Higher absolute RoCoF values lead to faster convergence, but do not produce a significant undershoot.

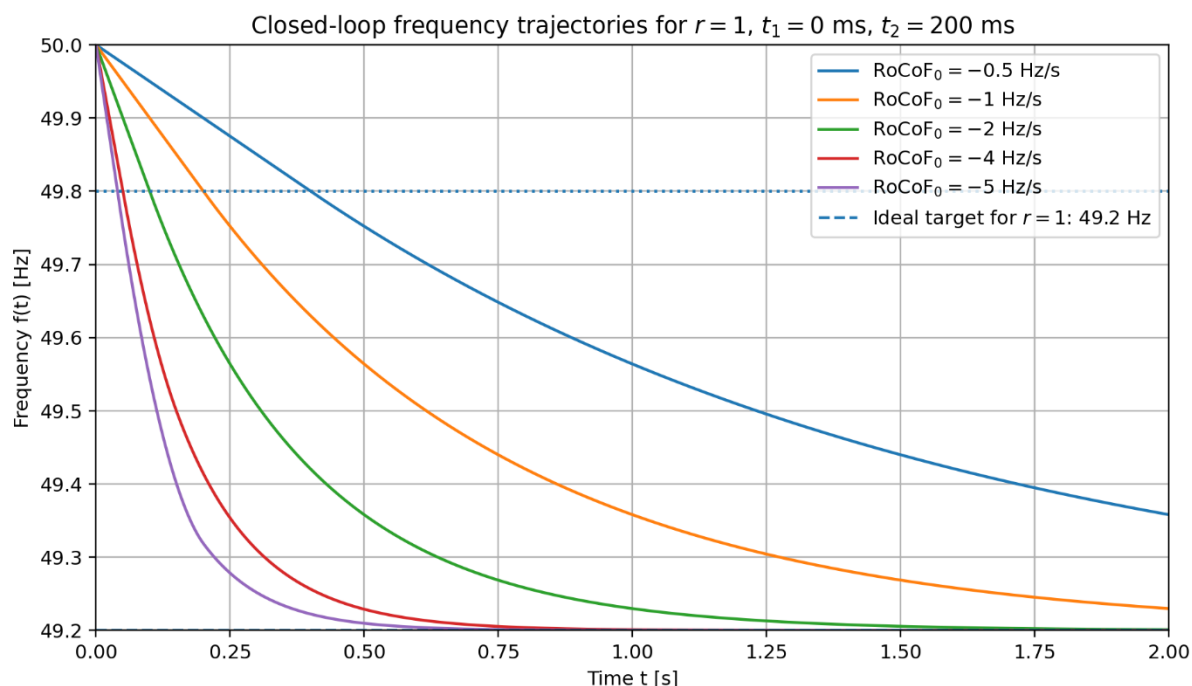


Figure 4-6 – Frequency trajectories for different initial RoCoF values for $r=1$, $t_1=0$ ms, $t_2=200$ ms

With an activation delay of 50 ms and full activation within 300 ms, the response remains adequate for the lower RoCoF cases. However, the trajectories corresponding to -4 Hz/s and -5 Hz/s fall below the ideal equilibrium target before the full FFR output becomes available. The frequency is subsequently arrested at approximately 49.1 Hz and 48.93 Hz, respectively.

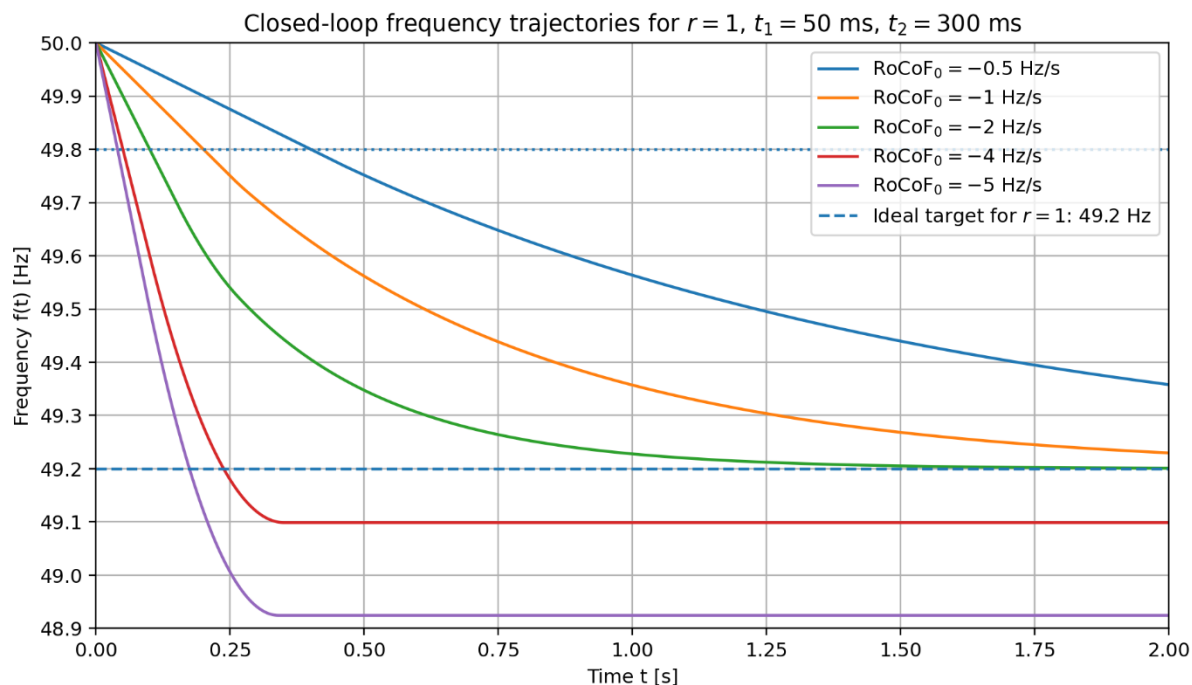


Figure 4-7 – Frequency trajectories for different initial RoCoF values for $r=1$, $t_1=50$ ms, $t_2=300$ ms

The least favourable setting, with an activation delay of 100 ms and full activation within 400 ms, produces a substantially deeper frequency decline. For initial RoCoF values of -4 Hz/s and -5 Hz/s, the frequency is arrested at approximately 48.8 Hz and 48.55 Hz, respectively. This demonstrates that the

same installed FFR capacity can result in significantly different frequency performance depending on the speed of its delivery.

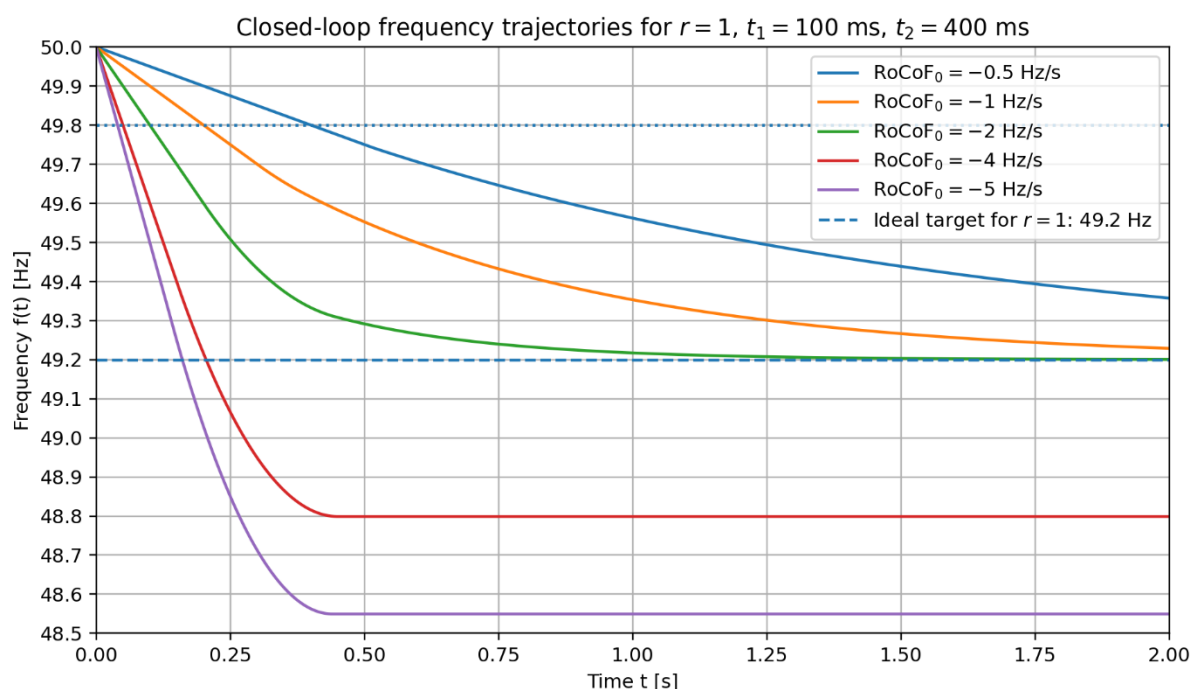


Figure 4-8 – Frequency trajectories for different initial RoCoF values for $r=1$, $t_1=100$ ms, $t_2=400$ ms

The analysis confirms that sufficient FFR capacity alone does not guarantee an acceptable frequency response. For high-RoCoF events, activation delay and rise time become critical design parameters. The required FFR performance should therefore be specified and assessed jointly in terms of available capacity, initial RoCoF, activation delay and full-activation time.

4.2.3 Sensitivity to the time parameters

This sensitivity analysis is a different perspective continuation of the previous subchapter. It evaluates the influence of the FFR activation delay and full-activation time for different initial RoCoF values. The disturbance-to-FFR ratio is maintained at ($r=1$), meaning that the available FFR capacity is equal to the disturbance size.

Once again, three representative response settings are considered: a fast response with no activation delay and full activation within 200 ms, an intermediate response with a 50 ms delay and full activation within 300 ms, and a slower response with a 100 ms delay and full activation within 400 ms.

For initial RoCoF values of -0.5 Hz/s and -1 Hz/s, the influence of the time parameters is very limited. The frequency declines relatively slowly, providing sufficient time for all three FFR responses to develop. The resulting trajectories are therefore almost identical.

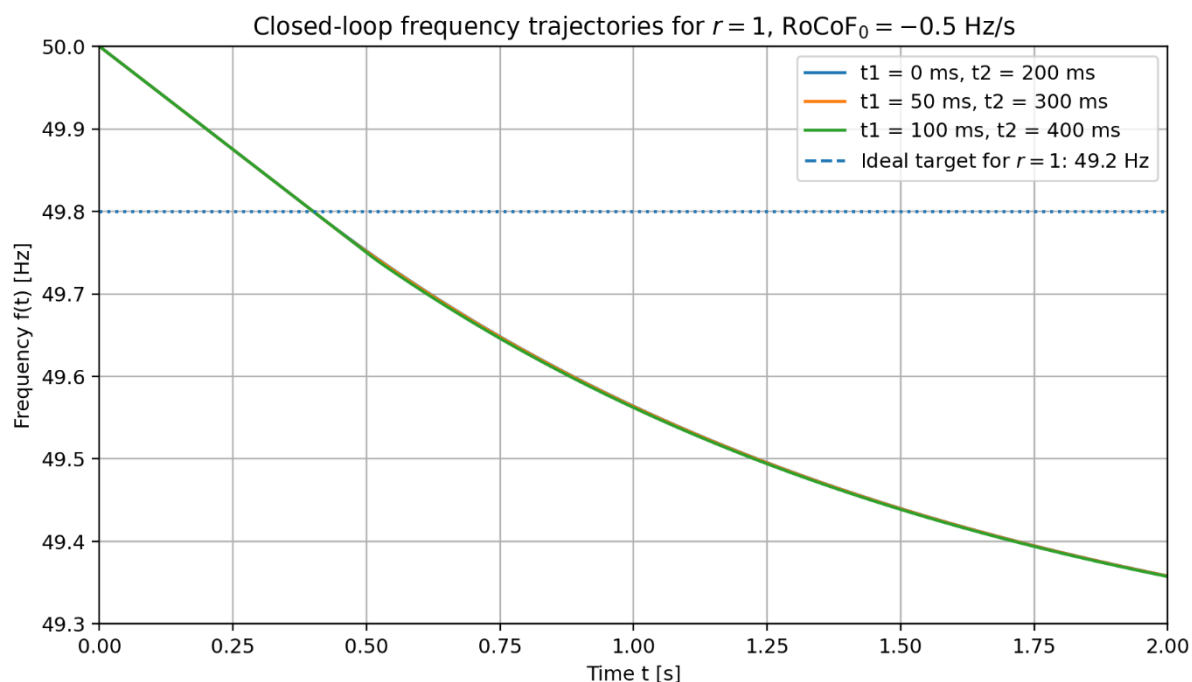


Figure 4-9 – Frequency trajectories for different time parameters and initial RoCoF of -0,5 Hz/s

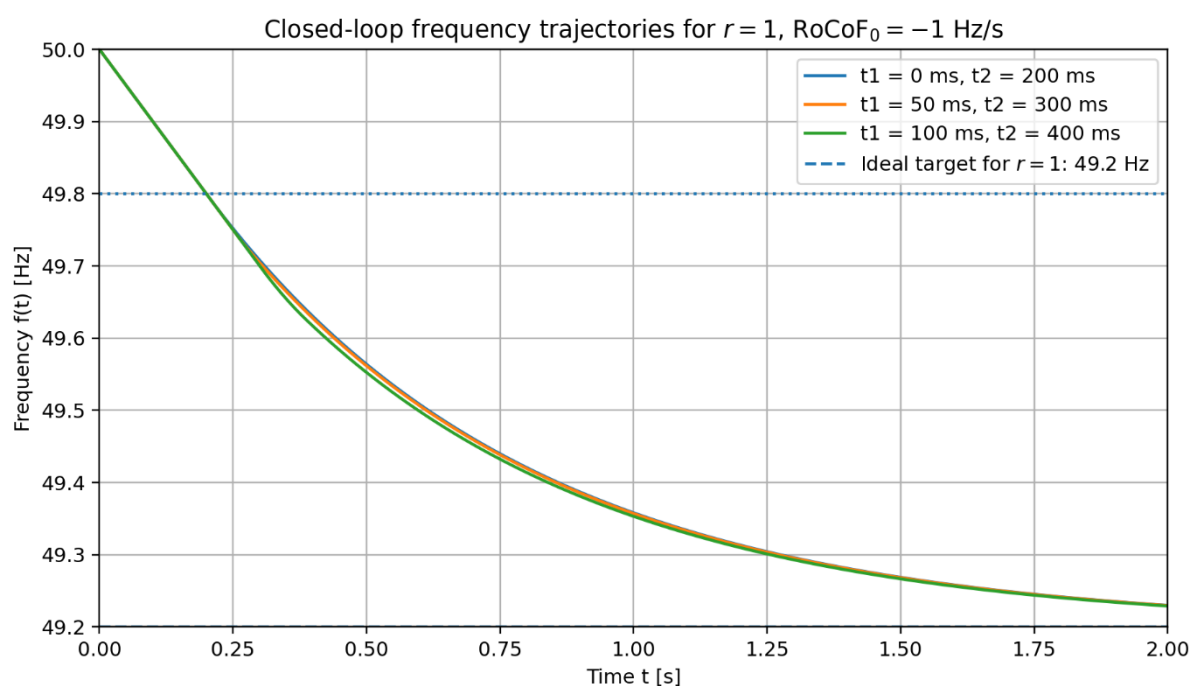


Figure 4-10 – Frequency trajectories for different time parameters and initial RoCoF of -1 Hz/s

At an initial RoCoF of -2 Hz/s , the differences become more visible but remain moderate. The slower response causes a slightly faster approach towards the ideal equilibrium target, reflecting the greater frequency loss accumulated during the activation and ramp-up period.

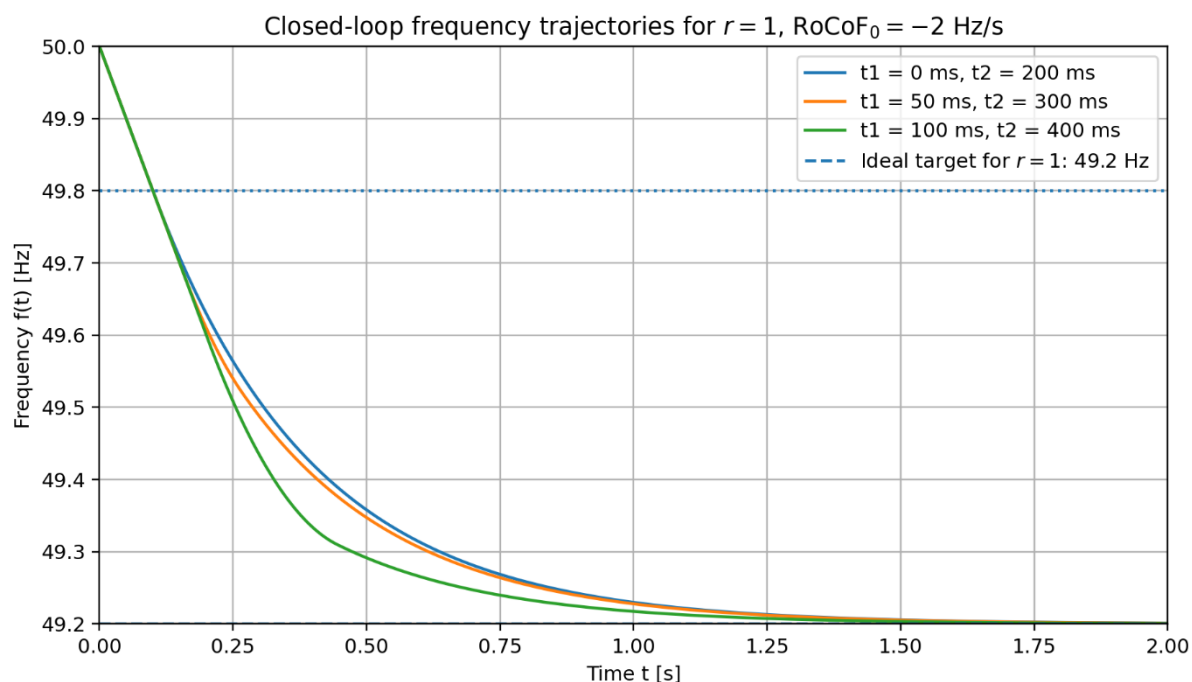


Figure 4-11 – Frequency trajectories for different time parameters and initial RoCoF of -2 Hz/s

The time parameters become critical for the high-RoCoF cases. At -4 Hz/s , the fastest response arrests the frequency close to the ideal target of 49.2 Hz, while the intermediate and slow responses result in arrest frequencies of approximately 49.1 Hz and 48.8 Hz, respectively. At -5 Hz/s , the corresponding arrest frequencies are approximately 49.2 Hz, 48.93 Hz and 48.55 Hz.

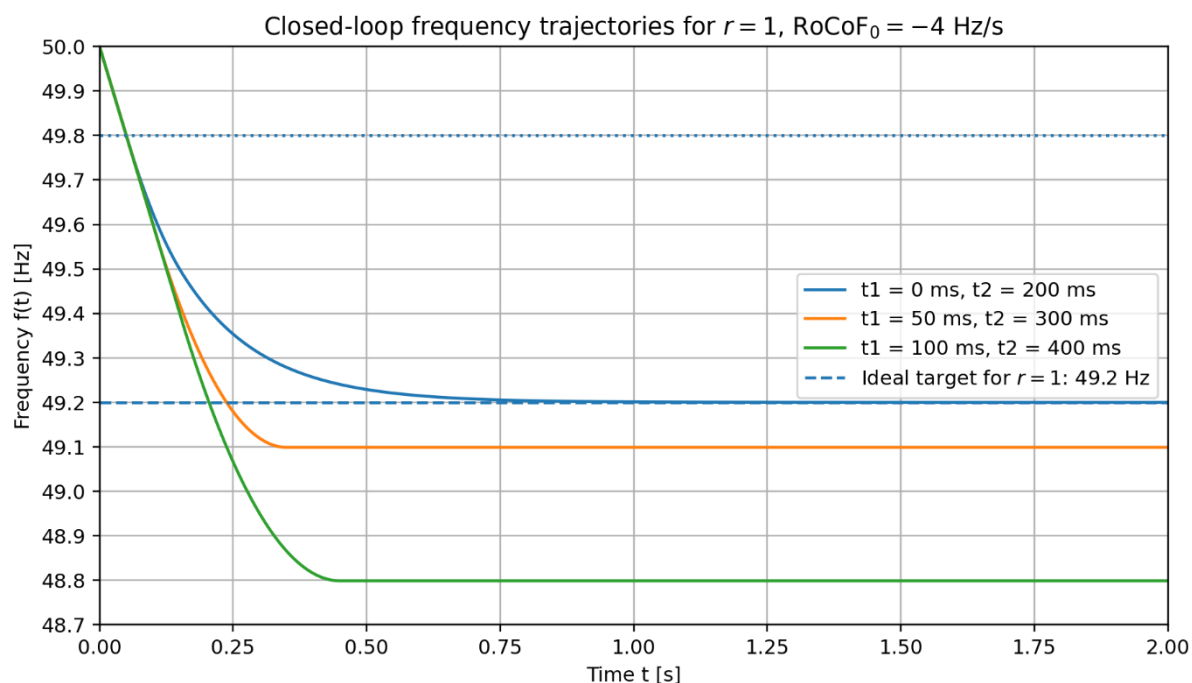


Figure 4-12 – Frequency trajectories for different time parameters and initial RoCoF of -4 Hz/s

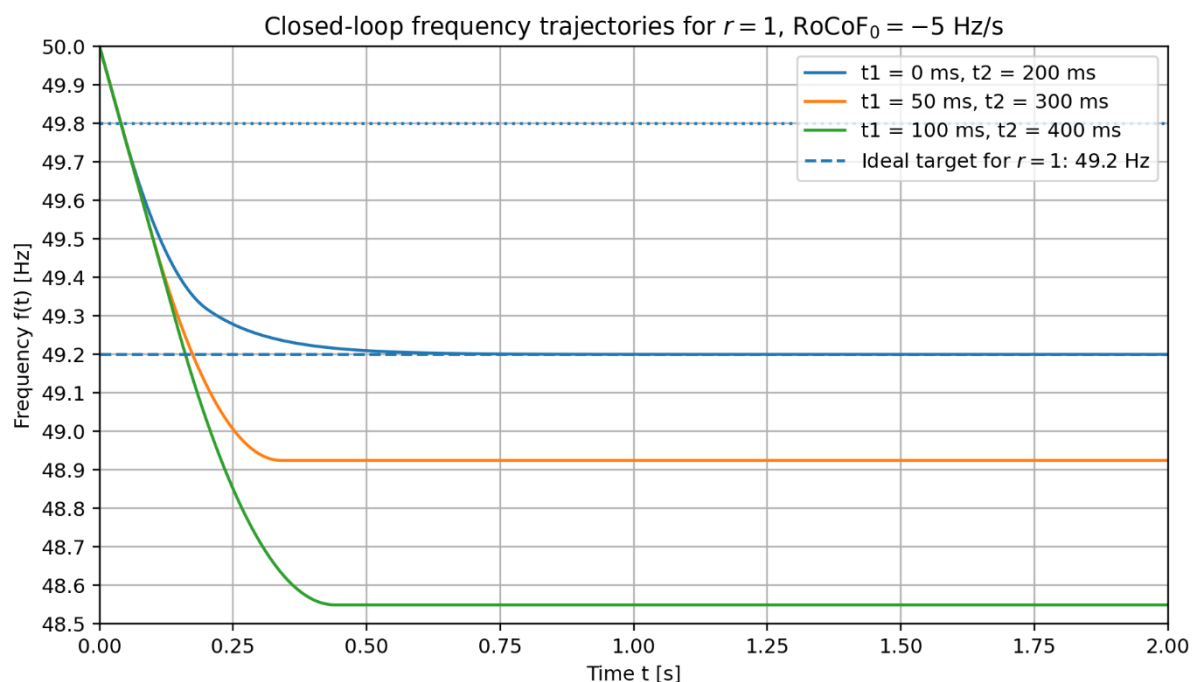


Figure 4-13 – Frequency trajectories for different time parameters and initial RoCoF of -5 Hz/s

The results demonstrate that the impact of the activation delay and full-activation time increases strongly with the absolute value of the initial RoCoF. In low-RoCoF conditions, differences of several tens or hundreds of milliseconds have only a minor effect. In high-RoCoF conditions, the same delays can produce a substantial deterioration of the frequency nadir and arrest frequency.

4.2.4 Nadir sensitivity

This section consolidates the influence of the disturbance-to-FFR ratio, initial RoCoF, activation delay and full-activation time on the frequency nadir. The results confirm that the disturbance-to-FFR ratio is the primary structural parameter, while the time parameters determine how effectively the available FFR capacity can be delivered during the initial frequency transient.

For disturbance-to-FFR ratios of 0.5 and 1, the available FFR capacity is sufficient to arrest the frequency. The nadir remains relatively stable across the analysed RoCoF range, although higher absolute RoCoF values increase the effect of activation delay and limited ramping capability. The case with a ratio of 0.5 is the most robust because the available FFR capacity exceeds the disturbance.

For a disturbance-to-FFR ratio of 1.5, the available FFR capacity is insufficient. The frequency cannot be arrested by FFR alone and continues to decline after full activation. Consequently, the values shown in the figure represent the minimum frequency reached within the analysed simulation period rather than a true frequency nadir. Their magnitude therefore also depends on the selected simulation horizon.

The impact of the r -ratio is furthermore analysed in the next subchapter of the sensitivity analysis.

The activation delay has only a minor influence under moderate RoCoF conditions. At an initial RoCoF of -2 Hz/s, increasing the delay from 0 to 100 ms does not materially reduce the nadir. At -4 Hz/s and -5 Hz/s, however, the same delay causes a clear deterioration, reducing the nadir to approximately 49.0 Hz and 48.8 Hz, respectively.

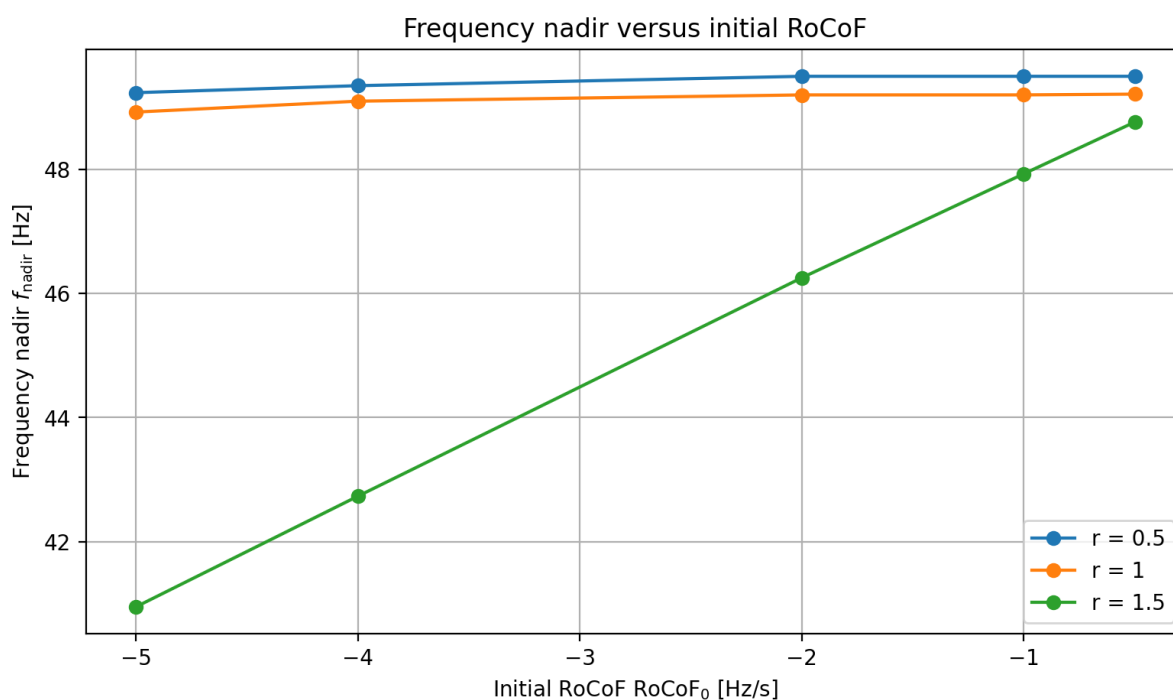


Figure 4-14 – Frequency nadir for different initial RoCoF and disturbance-to FFR ratios

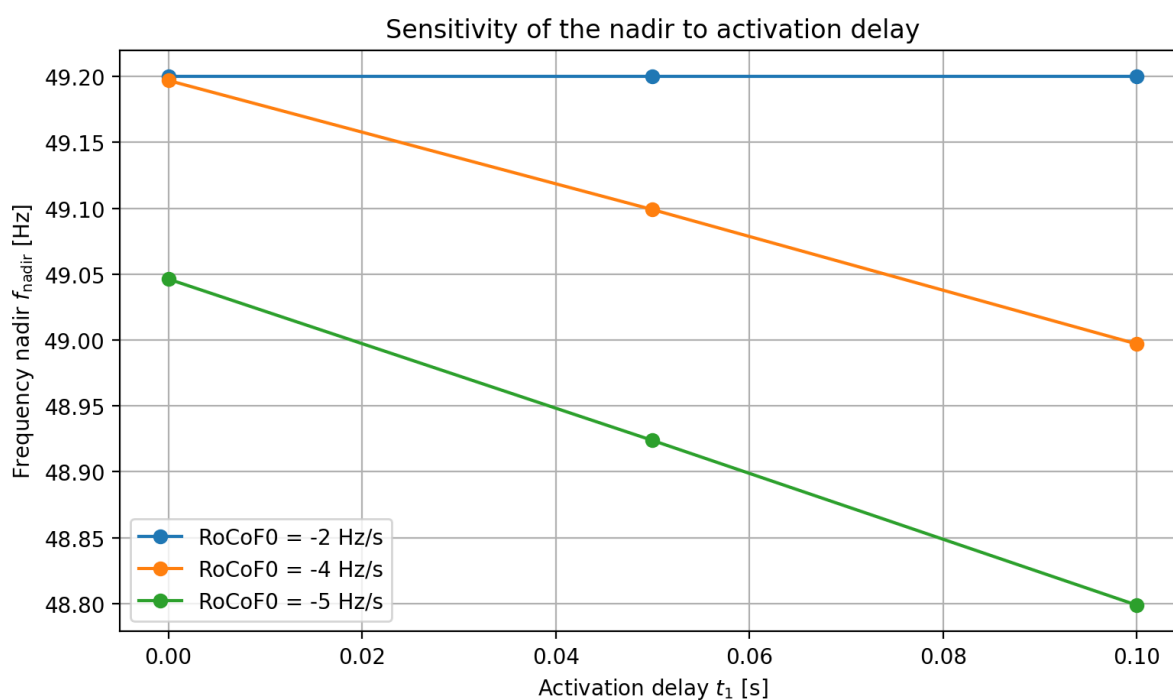


Figure 4-15 – Sensitivity of the nadir to activation delay t_1

A similar effect is observed for the full-activation time. Increasing it from 200 ms to 400 ms has almost no impact at -2 Hz/s but significantly lowers the nadir under high-RoCoF conditions. At -4 Hz/s, the nadir decreases from approximately 49.2 Hz to 48.9 Hz, while at -5 Hz/s it decreases from approximately 49.18 Hz to 48.68 Hz.

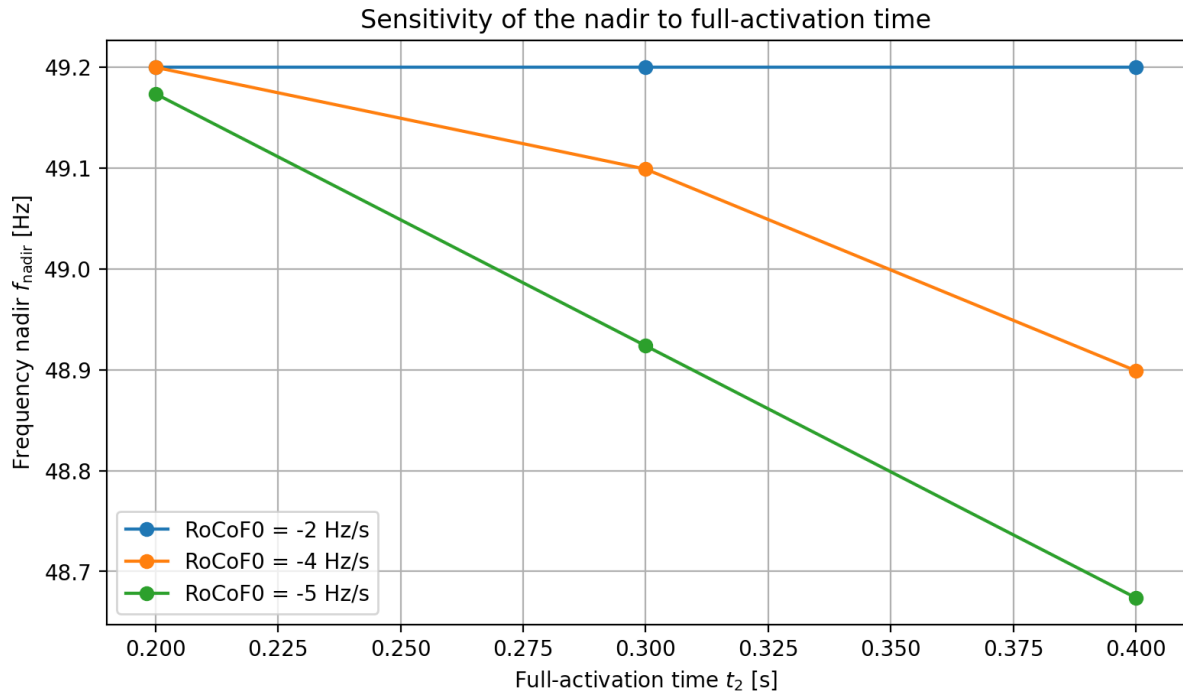


Figure 4-16 – Sensitivity of the nadir to activation delay t_2

The analysis demonstrates that FFR capacity adequacy must be assessed before response speed. If the available capacity is insufficient, faster activation cannot establish frequency arrest. Where sufficient capacity is available, the activation delay and full-activation time become decisive under high-RoCoF conditions. FFR requirements should therefore be defined against the expected maximum RoCoF and the minimum acceptable frequency nadir, with capacity and delivery speed assessed jointly.

4.2.5 Disturbance-to-FFR ratio r impact

The ratio r determines whether the available FFR capacity is sufficient to compensate for the disturbance and arrest the frequency deviation.

It was established that for an underfrequency event, the ideal equilibrium is reached when the activated FFR power exactly compensates for the disturbance:

$$P_{\text{FFR}} = \Delta P_{\text{dist}}.$$

Within the proportional part of the proposed FFR characteristic, the corresponding ideal equilibrium frequency is

$$f_{\text{eq}}^{\text{ideal}} = 50 - (0.2 + 0.6r) \text{ Hz},$$

which is valid for

$$0 \leq r \leq 1.$$

Case $r = 0.5$

In this case, the available FFR capacity is twice the disturbance size:

$$P_{\text{FFR}}^{\text{max}} = 2\Delta P_{\text{dist}}.$$

Only half of the available FFR capacity is required to compensate for the disturbance. The ideal equilibrium frequency is therefore

$$f_{eq}^{ideal} = 50 - (0.2 + 0.6 \cdot 0.5) \text{ Hz} = 49.5 \text{ Hz}.$$

This is the most robust of the analysed cases. Even under strong RoCoF, the available FFR capacity provides a substantial reserve margin, the reserve is fundamentally large enough to counteract the disturbance, and the frequency can be arrested before the FFR output reaches full saturation. The resulting performance is therefore mainly influenced by the activation delay and ramp-rate limitations.

Case $r = 1.0$

In this case, the maximum available FFR capacity is equal to the disturbance:

$$P_{FFR}^{max} = \Delta P_{dist}.$$

The ideal equilibrium frequency is

$$f_{eq}^{ideal} = 50 - (0.2 + 0.6 \cdot 1) \text{ Hz} = 49.2 \text{ Hz}.$$

This represents the limiting case for frequency arrest by FFR alone. The entire available FFR capacity must be activated to compensate for the disturbance. Consequently, no additional capacity margin remains to compensate for activation delay or limited ramping capability.

Under more severe dynamic conditions, the actual frequency nadir may temporarily fall below the ideal equilibrium target before the full FFR response is delivered. Namely in slow events, it performs adequately. In very fast and severe events, however, the delay and ramp-rate deficit are no longer masked by excess reserve, so the minimum frequency can drop significantly below 49.2 Hz before the response catches up.

Case $r = 1.5$

In this case, the disturbance exceeds the maximum available FFR capacity:

$$\Delta P_{dist} > P_{FFR}^{max}.$$

Even after full FFR activation, a residual active-power imbalance remains. Therefore, no equilibrium frequency exists within the inertia-plus-FFR-only model.

After the FFR output reaches saturation, the frequency slope is

$$\dot{\Delta f}_{sat} = \frac{f_0}{2HS_{base}} (-\Delta P_{dist} + P_{FFR}^{max}).$$

The maximum FFR capacity can be written as

$$P_{FFR}^{max} = \frac{\Delta P_{dist}}{r}.$$

Therefore,

$$\dot{\Delta f}_{sat} = -\frac{f_0 \Delta P_{dist}}{2HS_{base}} \left(1 - \frac{1}{r}\right).$$

The initial RoCoF is

$$\text{RoCoF}_0 = -\frac{f_0 \Delta P_{\text{dist}}}{2HS_{\text{base}}}.$$

Consequently, the post-saturation frequency slope for an underfrequency event is

$$\dot{f}_{\text{sat}} = -|\text{RoCoF}_0| \left(1 - \frac{1}{r}\right).$$

For $r = 1.5$,

$$\dot{f}_{\text{sat}} = -|\text{RoCoF}_0| \left(1 - \frac{1}{1.5}\right) = -\frac{|\text{RoCoF}_0|}{3}.$$

Thus, for example if

$$\text{RoCoF}_0 = -2 \text{ Hz/s} \Rightarrow \dot{f}_{\text{sat}} \approx -0.667 \text{ Hz/s},$$

And if

$$\text{RoCoF}_0 = -5 \text{ Hz/s} \Rightarrow \dot{f}_{\text{sat}} \approx -1.667 \text{ Hz/s}.$$

The resulting design condition remains

$$r > 1 \Rightarrow \text{FFR alone cannot arrest the frequency}$$

The graphical representation of the sensitivity analysis of the disturbance-to-FFR ratio is shown at the following figure:

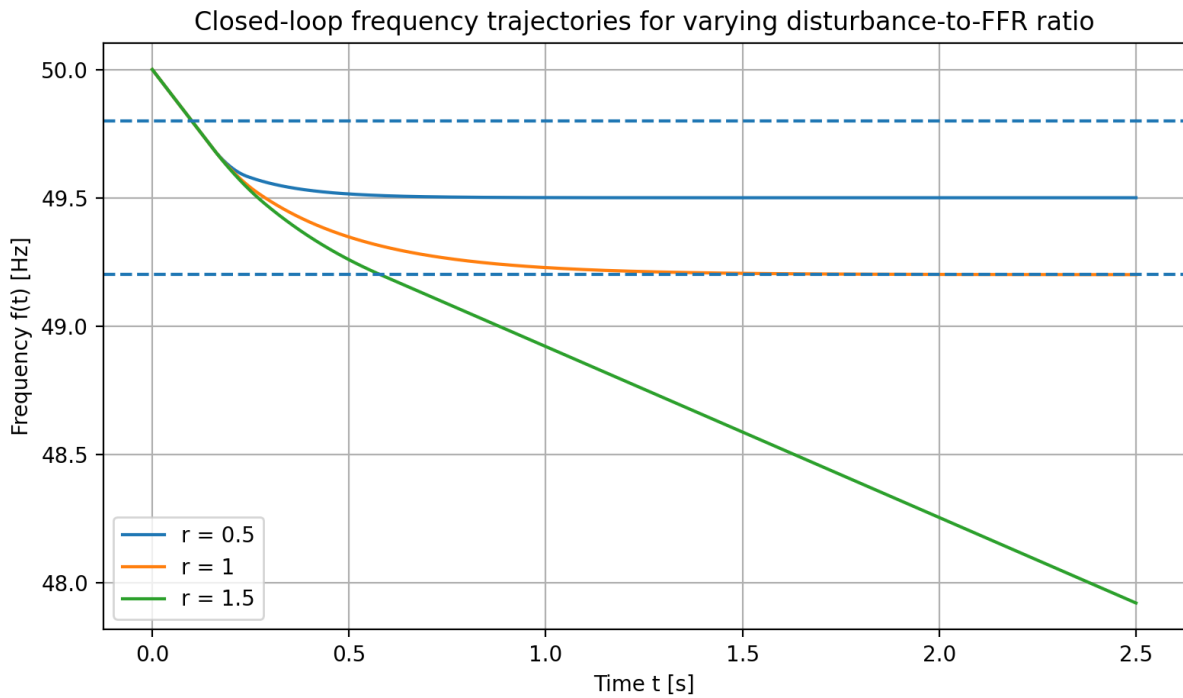


Figure 4-17 – Sensitivity analysis of the disturbance-to-FFR ratio

4.3 FFR planning

The purpose of this section is to define a simple and transparent screening framework for estimating the total Fast Frequency Response (FFR) capacity for different operating states of a control area. The framework is intentionally limited to the initial electromechanical frequency transient. It supports first-step planning, scenario screening, and interpretation, but it does not replace detailed time-domain validation of the FFR response.

The main planning variables are:

- the effective inertia constant of the control area,
- the credible active-power disturbance,
- the associated initial RoCoF₀,
- the disturbance-to-FFR ratio r and the total available FFR capacity.

The objective is to provide a compact planning process for estimating a reference FFR capacity envelope across different system states, including low-inertia conditions and severe disturbances. Final capacity requirements must subsequently be confirmed by detailed dynamic simulations.

Analytical basis

For a single-machine equivalent representation of the control area, the initial swing equation is written as

$$\frac{2H}{f_0} \frac{df}{dt} = -\Delta P_{\text{dist}}$$

where:

- f_0 is the nominal system frequency,
- $H = H_{\text{sys}}$ [s] is the equivalent inertia coefficient of the system in the control area of interest:

$$\begin{aligned} H = H_{\text{sys}} &= \frac{\sum_{i=1}^k H_{i,\text{conv}} S_{i,\text{conv}} + \sum_{j=1}^k H_{j,\text{synth}} S_{j,\text{synth}}}{\sum_{i=1}^k S_{i,\text{conv}} + \sum_{j=1}^k S_{j,\text{synth}}} = \\ &= \frac{\sum_{i=1}^k H_{i,\text{conv}} S_{i,\text{conv}} + \sum_{j=1}^k H_{j,\text{synth}} S_{j,\text{synth}}}{S_{\text{sys},\text{base}}} \end{aligned}$$

which includes the conventional inertia constants $H_{i,\text{conv}}$, and also synthetic inertia constants $H_{j,\text{synth}}$, as defined in the sensitivity analysis, and

- ΔP_{dist} is the net active-power imbalance immediately after the disturbance.

We revisit the disturbance-to-FFR ratio as

$$r = \frac{\Delta P_{\text{dist}}}{P_{\text{FFR}}^{\text{max}}}.$$

The reference case adopted in this screening framework is

$$r = 1,$$

which implies

$$\Delta P_{\text{dist}} = P_{\text{FFR}}^{\text{max}}.$$

These relations yield the reference FFR capacity-sizing relation:

$$P_{\text{FFR}}^{\text{max}} = \frac{2H |\text{RoCoF}_0|}{f_0}.$$

If the result is required in MW, the reference total FFR capacity becomes

$$P_{\text{FFR}}^{\text{max}}[\text{MW}] = \left(\frac{2H |\text{RoCoF}_0|}{f_0} \right) S_{\text{sys,base}}[\text{MW}].$$

The equations above do not imply that FFR reduces the initial RoCoF. The initial RoCoF is established immediately after the disturbance, before a threshold-based FFR response is delivered. Under the reference assumption $r = 1$, the maximum FFR capacity is simply set equal to the credible disturbance size; the resulting relation is therefore a capacity-sizing benchmark rather than a causal representation of the effect of FFR on the initial RoCoF.

A ratio below one represents an FFR capacity margin relative to the disturbance, while a ratio above one indicates that FFR alone cannot fully compensate for the disturbance in the simplified inertia-plus-FFR model.

These equations provide the analytical basis for the planning interpretations presented below.

Interpretation of the FFR planning through the prism of RoCoF₀-H relation

The RoCoF₀-H graphs (Figure 4-18) represent the relation

$$\text{RoCoF}_0(H) = -\frac{f_0}{2H} \left(\frac{P_{\text{FFR}}^{\text{max}}}{S_{\text{sys,base}}} \right)$$

for different reference FFR capacity shares under the assumption $r = 1$. Each curve therefore also represents a disturbance of the same per-unit magnitude as the plotted FFR capacity. The curves are hyperbolic because, for a fixed disturbance, the magnitude of the initial RoCoF is inversely proportional to the inertia constant.

In planning terms, the graph answers the following question:

For a disturbance equal to the planned FFR capacity, what acceptable initial RoCoF is associated with the current inertia state of the control area?

The graph shows that the same disturbance produces a steeper initial RoCoF when effective inertia is lower. This reduces the time available for the FFR response to develop and may require faster activation, additional FFR capacity margin, additional effective inertia, or a combination of these measures. However, additional threshold-based FFR capacity does not, by itself, reduce the initial RoCoF.

In addition to moderate reference levels, the graph includes FFR capacity shares of 16%, 32%, and 40% of $S_{\text{sys,base}}$. These values are intended for stress-test interpretation, including severe events such as system splitting or blackout-related islanding – they indicate the order of magnitude associated with disturbances representing a large fraction of the control-area base power.

The RoCoF₀-H representation is most useful when the planner starts with a credible disturbance or reference FFR capacity envelope and evaluates the resulting RoCoF exposure across different inertia states.

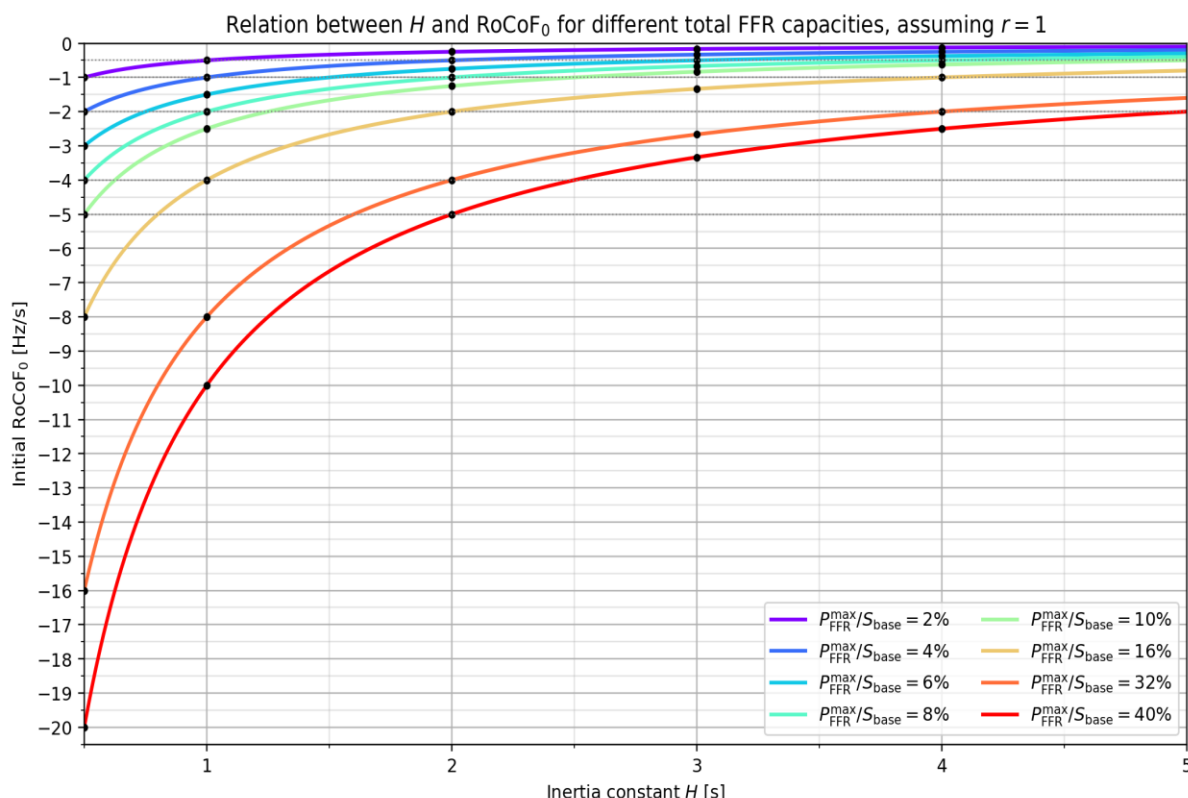


Figure 4-18: Relation between H and RoCoF_0 for different reference FFR capacities

The graph can be used as a first-step planning map:

1. select the operating state and its effective inertia constant H ,
2. select the credible disturbance or the corresponding reference FFR capacity under $r = 1$,
3. read the associated initial RoCoF ,
4. assess whether the resulting RoCoF exposure and the available response time are acceptable for that operating state.

This graph family is particularly useful for comparing present, future, and stressed operating conditions. It enables a direct comparison of high- and low-inertia states for the same disturbance envelope and quantifies the resulting change in initial RoCoF .

Interpretation of the FFR planning through the prism of RoCoF_0 -FFR relation for different inertia constants H of the control area

The RoCoF_0 -FFR capacity graphs present the same analytical relation from the inverse perspective. Under the reference assumption $r = 1$, they show the FFR capacity required to fully cover a disturbance that would produce a selected initial RoCoF for a given inertia constant.

From the planning formula,

$$\frac{P_{\text{FFR}}^{\text{max}}}{S_{\text{sys,base}}} = \frac{-2H |\text{RoCoF}_0|}{f_0},$$

the reference FFR capacity increases linearly with both the inertia constant H and the selected RoCoF magnitude. This is because a larger disturbance is required to produce the same RoCoF in a system with higher inertia.

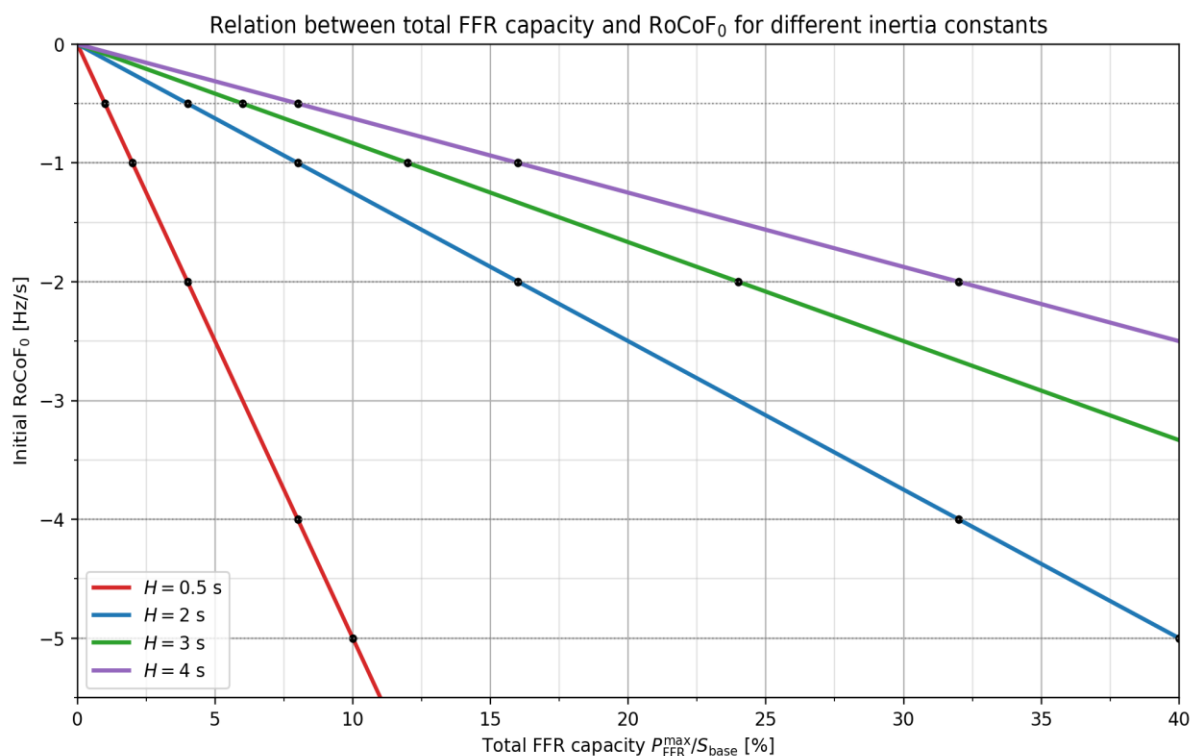


Figure 4-19: Relation between total FFR capacity and RoCoF₀ for different inertia constants

In planning terms, this graph answers the following question:

For a given inertia state and selected initial RoCoF, what disturbance size - and therefore what FFR capacity under $r = 1$ - is implied?

The individual and combined plots for

$$H = \{0.5, 2, 3, 4\} \text{ s}$$

show that the same initial RoCoF level corresponds to different disturbance sizes and therefore different reference FFR capacities.

At low inertia, relatively small disturbances can produce severe RoCoF values. At higher inertia, the same RoCoF corresponds to a larger disturbance and therefore a larger reference FFR capacity under $r = 1$. The graph should not be interpreted as low-inertia operation requiring less frequency support; instead, it shows that severe RoCoF exposure occurs at smaller disturbance sizes and places stronger requirements on response speed and dynamic performance.

This graph family is another, more practical view for first-cut capacity sizing because it starts from the inertia state and the selected RoCoF scenario and returns the corresponding reference FFR capacity. The highlighted reference points

$$\text{RoCoF}_0 = \{-0.5, -1, -2, -4, -5\} \text{ Hz/s}$$

provide a structured disturbance-severity range from moderate to extreme cases.

Once the inertia state and credible disturbance scenario have been established, the reference $r = 1$ capacity can be read from the graph or calculated directly. The RoCoF₀-FFR capacity view is therefore suitable for high-level scenario planning and initial procurement discussions, subject to subsequent dynamic validation.

4.3.1 Proposed planning process for total FFR capacity

The proposed first-step planning process is as follows.

Step 1: define the system state

Estimate the effective inertia constant H of the control area for the operating state of interest. Classical (conventional) synchronous inertia may be included directly. Converter-based or synthetic-inertia contributions should be included in an equivalent inertia value only where their response within the initial RoCoF time window has been demonstrated and represented consistently; otherwise, they should be modelled separately in the dynamic validation stage.

Step 2: define the system base

Define $S_{\text{sys,base}}$ consistently. Depending on the study scope, it may represent total online net generation, total demand, or another explicitly defined control-area scaling power which is used for defining the equivalent inertia constant of the control area. The selected definition must remain unchanged across the compared scenarios.

Step 3: define the credible disturbance set

Define the credible disturbance set independently from the available FFR capacity. The set may include ordinary operating contingencies and severe stress-test events, such as system splitting or islanding. The reference assumption $r = 1$ is applied only after the disturbance set has been established.

Step 4: define the RoCoF planning levels and coverage ratio

Select the initial RoCoF levels used for screening and define the disturbance-to-FFR ratio applied in each planning case. The reference value $r = 1$ represents complete disturbance coverage without additional FFR capacity margin. In this study, the following RoCoF set is used:

$$\text{RoCoF}_0 = \{-0.5, -1, -2, -4, -5\} \frac{\text{Hz}}{\text{s}}.$$

Step 5: calculate the reference total FFR capacity

Use the reference planning equation

$$\frac{P_{\text{FFR}}^{\text{max}}}{S_{\text{sys,base}}} = \frac{2H |\text{RoCoF}_0|}{f_0}$$

to determine the FFR capacity share corresponding to the selected inertia and RoCoF scenario under $r = 1$. The result is a screening benchmark and should not be interpreted as the final procurement volume.

Where procurement quantities are expressed in MW, use

$$P_{\text{FFR}}^{\text{max}}[\text{MW}] = \left(\frac{2H |\text{RoCoF}_0|}{f_0} \right) S_{\text{sys,base}}[\text{MW}].$$

The following table summarises the reference total FFR capacity as a percentage of $S_{\text{sys,base}}$ for selected values of H and RoCoF_0 under the assumption $r = 1$.

Table 4-1: Reference table for FFR planning for selected inertia constants H and initial RoCoF₀ values under $r = 1$

	RoCoF ₀ = -0.5 Hz/s	RoCoF ₀ = -1 Hz/s	RoCoF ₀ = -2 Hz/s	RoCoF ₀ = -4 Hz/s	RoCoF ₀ = -5 Hz/s
$H = 0.5$ s	1.0%	2.0%	4.0%	8.0%	10.0%
$H = 1$ s	2.0%	4.0%	8.0%	16.0%	20.0%
$H = 2$ s	4.0%	8.0%	16.0%	32.0%	40.0%
$H = 3$ s	6.0%	12.0%	24.0%	48.0%	60.0%
$H = 4$ s	8.0%	16.0%	32.0%	64.0%	80.0%

The table should be used as a screening aid. Each value represents the capacity that equals the disturbance associated with the selected H and RoCoF₀ under $r = 1$. Final FFR procurement quantities must be derived from credible disturbance scenarios and confirmed through detailed dynamic assessment.

Step 6: validate dynamically

Validate the first-cut capacity estimate using the detailed closed-loop FFR model, but most importantly with simulations in a dedicated dynamic model environment. The validation should include the static P-f characteristics, activation delay, full-activation time, ramp-rate limitation, energy sufficiency, damping, interaction with FCR and other control layers, and relevant network constraints.

4.3.1.1 Advantages and limitations

The main strength of the method is its transparency. The analytical relation between inertia, disturbance size, FFR capacity, and initial RoCoF is explicit, easy to interpret, and suitable for first-step planning discussions.

The method also supports rapid comparison of present and future operating states. It shows how changes in inertia and disturbance severity alter the initial RoCoF exposure and the reference FFR capacity required to cover the disturbance under a selected planning ratio.

A further advantage is that validated inertia-like contributions may be represented through an effective parameter H . This can simplify strategic scenario screening while preserving the need for detailed dynamic modelling.

However, certain limitations remain. First, the method is highly aggregated. It does not represent internal network constraints, spatial distribution of inertia and FFR, inter-area oscillations, voltage dynamics, protection behavior, or the detailed response of individual providers.

This approach describes the disturbance-to-inertia relation through the initial RoCoF, but it does not determine the full frequency trajectory, frequency nadir, arrest frequency, recovery phase, or interaction with FCR and load damping. It must also not be interpreted as showing that threshold-based FFR reduces the initial RoCoF.

Finally, $r = 1$ is a transparent reference case rather than a universal planning requirement. Actual planning may require $r < 1$ to provide additional capacity margin, while $r > 1$ indicates that FFR alone cannot fully compensate for the disturbance in the simplified model. Simulations are inevitable.

4.3.2 Relevance of ENTSO-E Project Inertia Phase II to FFR planning

The proposed FFR planning framework should be considered within the broader system-resilience approach developed by ENTSO-E under Project Inertia Phase II. The project addresses the long-term reduction of system inertia in the Continental Europe synchronous area and the corresponding deterioration of frequency resilience, particularly following severe system-split events. [36], [37], [38], [39]

Project Inertia distinguishes between foundational measures and enhanced response measures. Foundational measures address the root cause of reduced frequency resilience by maintaining sufficient kinetic energy, or an equivalent inertial contribution, before a disturbance occurs. Their main purpose is to limit the speed and magnitude of the initial frequency excursion and improve the survivability of the resulting islanded subsystems.

Enhanced response measures act during or after the disturbance and improve the ability of the system and connected equipment to withstand high frequency gradients, contain the frequency nadir or zenith, and mitigate the consequences within the affected subsystem. Within this deliverable, threshold-based FFR is treated as a complementary enhanced response measure. It does not replace sufficient inertia and, because its activation begins only after the defined frequency-deviation threshold is reached, it does not modify the true initial RoCoF.

The treatment of initial RoCoF in Project Inertia Phase II is particularly relevant to the present planning framework. For system-split assessments, ENTSO-E evaluates the global initial RoCoF at the centre of inertia of each resulting subsystem. Global Severe Splits are identified as split cases in which the initial RoCoF exceeds 1 Hz/s in both resulting subsystems. This initial value is used as an objective indicator of the scale and severity of the disturbance.

The report also emphasizes that the initial RoCoF should not be confused with the RoCoF values normally used for operational limits or equipment withstand assessments. Such limits are commonly evaluated over a 500 ms measurement window, whereas the instantaneous initial RoCoF may be significantly higher than the corresponding averaged value. Furthermore, local RoCoF values may be more severe than the global RoCoF evaluated at the centre of inertia. The initial RoCoF used in the simplified FFR planning framework should therefore be interpreted as a transparent system-level screening indicator rather than as a direct equipment-compliance criterion.

This distinction further clarifies the interaction between inertia and FFR. The effective inertia level determines the initial RoCoF and therefore the time available before the FFR activation threshold is reached. The available FFR capacity, activation delay and full-activation time then determine the subsequent frequency containment performance, including the frequency nadir and the ability to arrest the frequency deviation. Inertia and FFR should therefore be planned jointly, while retaining their different physical and temporal functions.

ENTSO-E recommends a bottom-up nodal approach for allocating minimum kinetic-energy requirements across Continental Europe. This approach is based on a minimum equivalent inertia constant at individual nodes and is considered transparent, monitorable and less dependent on predefined system-split configurations. The geographical distribution of kinetic energy is essential because the location and configuration of future system splits cannot be predicted.

A similar principle applies to FFR planning. Aggregate control-area dimensioning should be complemented by nodal and geo-electrical assessments. The total FFR capacity should be adequately dispersed to remain effective during national, regional and local islanding events and to avoid

excessive dependence on individual providers or network locations. Local frequency behavior and local RoCoF should be examined through detailed dynamic simulations, particularly where network separation may create weak or highly unbalanced subsystems.

As an initial no-regret target, ENTSO-E proposes that a minimum inertia constant of

$$H_{min} = 2 \text{ MWs/MVA}$$

should be reached in the Continental Europe synchronous area for 50% of the year by 2035. As a subsequent long-term target, all countries should ensure this minimum value for 90% of the year, subject to future reassessment. These values do not constitute FFR requirements, but they provide relevant external reference points for defining representative inertia scenarios in FFR planning.

System-split scenarios should remain an important part of the FFR resilience assessment, but they should not automatically determine the standard procurement quantity. ENTSO-E classifies system splits as out-of-range contingencies and retains the 3 000 MW reference incident for dimensioning FCR in Continental Europe. High FFR requirements obtained from severe split scenarios should therefore be interpreted primarily as stress-test values defining the outer resilience envelope. Their translation into procurement requirements should additionally consider event probability, available inertia, defense-plan actions, provider capability, technical feasibility and economic proportionality.

The resulting FFR planning process should first establish the expected equivalent of kinetic energy and equivalent inertia conditions for the operating state under consideration. The corresponding global initial RoCoF should then be estimated as a system-level screening parameter, while recognizing that local RoCoF may be more severe. The required FFR capacity and dynamic response should subsequently be determined based on the credible disturbance, activation threshold, response delay, full-activation time and acceptable frequency nadir. The final design should always be validated through detailed time-domain simulations that represent local network conditions, primary reserve deployment, protection actions and other relevant frequency-control processes.

4.3.3 FFR unit specifics

Unit-level requirements translate the total control area FFR requirement into technical and locational conditions for individual providers. The objective is not to maximize the FFR contribution of each unit, but to establish a sufficiently dispersed, observable and controllable portfolio that can deliver the required response without creating excessive dependence on individual providers or network locations.

4.3.3.1 Unit-level FFR capacity

For units used simultaneously for FFR and other operational or commercial purposes, the contracted FFR capacity should be limited relative to the rated active power of the unit. The following indicative values are proposed:

- minimum FFR capacity: 0.05 pu;
- preferred reference value: 0.16 pu;
- recommended upper limit: 0.32 pu.

FFR provision above 0.32 pu from an individual multifunctional unit is generally not recommended, as excessive concentration may reduce the geo-electrical dispersion and resilience of the total control-

area FFR portfolio. The proposed values should be confirmed through provider prequalification and system-level dynamic studies.

For units dedicated exclusively to FFR provision, the available FFR capacity may be determined primarily by the technical capability and techno-economic feasibility of the installation. Nevertheless, the TSO should also assess the unit location, network impact and concentration risk before accepting a large contribution from a single provider.

4.3.3.2 Eligible connection voltage level

Under the proposed initial framework, FFR participation should be limited to providers connected directly to the transmission system at 110 kV, 220 kV or 400 kV or simply the high-voltage levels in Continental Europe. Transmission-level connection supports direct TSO observability, performance verification and operational controllability of the service and directly applies the purpose of the FFR as an ancillary service.

Providers connected at medium- or low-voltage level (MV or LV, respectively) are not considered eligible during the initial development phase. Their inclusion would require additional TSO–DSO coordination, robust extensive monitoring and control infrastructure, and explicit management of distribution-network constraints. In distribution networks, active-power activation may also produce location-dependent interactions between active power, reactive power and voltage, particularly because of the relevant network impedance characteristics. In particular, in Slovenia, the ramping capabilities of the potential units for FFR provision, such as BESS, are highly limited according to the maximal permissible active power ramp of a few MW per minute, which contradicts the whole purpose of the FFR.

4.3.3.3 Potential classification of the FFR units

Classification of FFR providers is not considered mandatory. The TSO may introduce classifications where justified by the system topology, operational needs or available level of control.

A voltage-based classification may distinguish between:

- **Group I:** providers connected at 400 kV or 220 kV, primarily supporting system-level frequency stability;
- **Group II:** providers connected at 110 kV, with potentially stronger local or regional influence.

An additional classification may distinguish between grid-forming and grid-following operation. Grid-forming controls can operate without conventional phase-locked-loop-based synchronisation and may therefore provide a faster and more robust response, particularly under weak-grid or islanded conditions. Grid-following controls may include additional measurement and synchronisation dynamics, but they should remain eligible where the required FFR performance is demonstrated through prequalification. However, the main and primary purpose of the Grid-Forming controls is to provide an artificial or synthetic inertia prior to the capabilities of the market-based provision of FFR.

In any case, to preserve the non-discriminatory rules of the electricity market in Europe, it is highly important that the classification should be based on technical assessment and operational coordination rather than create unnecessary technology-based barriers. Compliance should ultimately be determined by the FFR delivered at the point of common coupling.

4.3.3.4 Geo-electrical dispersion and coordination with system defence and restoration plans

The total FFR capacity should be distributed across several providers and transmission network locations. Excessive concentration at a single node, generation site or provider should be avoided, even where the required total capacity could technically be supplied from one installation.

The required dispersion should be determined through dynamic simulations covering interconnected operation, system splits, national and regional islanding, weak-network conditions and restoration scenarios. The assessment should consider both the total control area response and the local frequency, voltage and power-flow effects associated with FFR activation.

The location and operational availability of FFR providers should be coordinated, where relevant, with the TSO's system defense plans on emergency and restoration of the electric power system. Particular attention should be given to network areas that may form an electrical island, support frequency management after system separation, assist active-power balancing or contribute to subsequent resynchronisation. Every area or potential island of interest must be particularly analysed focusing on the adequacy of the FFR capacities within them.

FFR should not automatically be considered a defense or restoration service under the Network Code on Emergency and Restoration (NC ER). Such a role would require explicit designation and appropriate legal or contractual arrangements. Nevertheless, alignment with the system defense and restoration plans can ensure that FFR settings, locations and activation behaviour support rather than conflict with the measures foreseen for emergency, blackout and restoration states.

4.3.3.5 Testing and validation

The provider and the TSO should jointly verify the proposed FFR capacity, control settings and activation behaviour before operational participation. The verification should cover the interaction with other frequency-control and protection functions. The testing should be verified and validated with appropriate simulation models.

Unit-level testing should be complemented by system-level dynamic simulations, i.e. electric power system operation study focusing on the probable FFR scenarios. A unit that satisfies its individual response requirements may still produce an undesirable system response if its capacity, location or control interaction is not appropriately coordinated with the wider FFR portfolio or other specific controls and governors in the electric power system.

Note: The local frequency at the point of common coupling should be sampled with a time interval of 20 ms or less, corresponding to a sampling rate of at least 50 samples per second. This resolution is required to detect the activation threshold reliably and to assess the FFR response within the proposed sub-second time requirements. A sampling interval of up to 20 ms may be considered the maximum acceptable value, providing that filtering, processing and measurement delays do not compromise the required activation performance. Appropriate filtering should suppress measurement noise without introducing excessive delay. The sampling interval should be considered together with the complete measurement, processing and activation chain.

4.3.3.6 LFSM response vs. FFR

A clear distinction must be made between the generation of an internal active power setpoint and the actual delivery of active power at the point of common coupling. The setpoint represents the target calculated by the controller after the relevant frequency condition has been detected. However, this target itself does not provide frequency support. The physical response additionally depends on

frequency measurement and filtering, controller processing, converter or governor dynamics, available power headroom, energy availability and plant-level limitations. From the power-system perspective, only the measurable change in active power delivered at the point of common coupling contributes to frequency containment. Internal setpoint calculation and signal processing constitute only part of the overall response time.

The proposed amended RfG 2.0 applies a similar distinction. The magnitude of an active-power setpoint change defines the reference test condition, while the response time refers to the resulting active-power increase or decrease. The relevant provisions also require that the start of the active-power response is not intentionally delayed. For electricity storage modules operating in LFSM-U-ESM, the proposed amended RfG 2.0 specifies a maximum response time of 0.5 s for a PPM-based storage module responding to a setpoint change equal to its full capacity. This response time excludes the additional time required to switch from consumption to generation or vice versa. The switching process must nevertheless be performed as fast as technically feasible. The 0.5 s requirement is therefore an important benchmark for BESS response, but it is not applicable to every LFSM function or provider category. Other provisions of the proposed amended regulation proposal allow response times of up to 2 s for the LFSM-O response of a PPM and up to 10 s for the general LFSM-U response. The applicable response time consequently depends on the operating direction, module classification and specific LFSM provision.

The proposed FFR service requires the active-power response to begin within 0–100 ms and to reach full activation within 200–400 ms. Compared with the 500 ms LFSM-U-ESM requirement for converter-connected storage, the proposed FFR full-activation time is moderately stricter and different in order of magnitude (setpoint change vs. active power output). Compared with the general LFSM requirements for other PPMs and synchronous units, however, FFR is substantially faster.

The details are shown in the following table:

Table 4-2: LFSM setpoint change v. FFR active power output response times

Module category	LFSM-O response time	LFSM-U response time	Proposed FFR response time
PPM other than an electricity storage module	≤ 2 s for an active power setpoint change equal to 50% of $P_{\max}$	≤ 10 s for an active power setpoint change equal to 50% of $P_{\max}$	The required active power output at the PCC should be reached within 400 ms or less
PPM-based electricity storage module, including BESS	≤ 2 s for an active power setpoint change equal to 50% of $P_{\max}$; no separate storage-specific LFSM-O response time is defined	≤ 0.5 s for an active power setpoint change equal to 1 pu of capacity under the dedicated LFSM-U-ESM requirement	The required active power output at the PCC should be reached within 400 ms or less

The principal distinction between FFR and LFSM is therefore not based only on response speed. LFSM represents a grid-connection capability that applicable modules must provide when the defined frequency conditions occur. Its actual response may depend on the operating point, available primary

energy, state of charge, technical limits and the time required to change between consumption and generation.

FFR is proposed as a dedicated ancillary service based on prequalified and explicitly reserved active-power capacity. A contracted FFR provider must maintain sufficient power headroom and energy availability to deliver the specified response within the complete dynamic envelope. Its availability, activation, delivered power and performance must be measurable and verifiable.

The activation characteristics of FFR and LFSM may overlap. For Continental Europe, the proposed amended RfG 2.0 defines a frequency-deviation threshold of 0.2 Hz for LFSM-O and LFSM-U. The proposed FFR service uses the same initial activation threshold because of the FCR market. FFR represents a faster and dedicated first-wave of response with a similar purpose to the LFSM responses.

The duration and deactivation principles also differ. LFSM follows the applicable frequency–power characteristic while the frequency condition persists and the technical capability remains available. FFR is intended to be designed as a short-duration response with a defined full-activation period and coordinated deactivation as slower frequency-control mechanisms become effective.

The decisive distinction is that LFSM defines a mandatory frequency-responsive capability, whereas FFR defines a faster, reserved, procured, prequalified and verifiable ancillary service. For both functions, compliance should ultimately be assessed through the active power delivered at the point of common coupling rather than through the speed of internal setpoint generation alone.

4.3.4 FFR dimensioning example in the Slovenian control area

Assume that the tolerable $\text{RoCoF}_0 = 2 \text{ Hz/s}$ and the system equivalent inertia constant $H = H_{\text{sys}} = 2 \text{ s}$ under $S_{\text{sys,base}} = P_{\text{net generation,CA}} = 2000 \text{ MW}$, yields:

$$P_{\text{FFR,SI}}^{\text{max}} = \left(\frac{2H_{\text{SI}} |\text{RoCoF}_0|}{f_0} \right) S_{\text{sys,base}} = 320 \text{ MW}$$

under the additional assumption of the FFR capability of covering the disturbance causing these conditions.

4.4 Market aspects and pricing

The introduction of FFR requires an appropriate market framework that reflects its specific technical and operational characteristics. Unlike conventional balancing energy products, FFR is primarily based on the continuous availability of reserved active-power capacity that can be activated within a very short time following a significant frequency deviation. Its value therefore arises mainly from assured availability, response speed and verified performance rather than from the volume of delivered energy.

During the initial development phase, FFR should be procured as a dedicated ancillary service within a single control area. Exchange or sharing between control areas is not considered at this stage. Closed, ex ante annual or multi-year agreements between the TSO and qualified providers represent a pragmatic initial procurement approach, particularly while the number of providers remains limited and a competitive bidding market could lack sufficient liquidity. Local competitive procurement mechanisms may be explored once adequate operational experience, provider diversity and market maturity have been established.

The remuneration framework should compensate providers for reserving capacity, maintaining the required availability and meeting the prescribed technical performance. It should also account for opportunity costs, control and communication requirements, testing obligations and the risk of non-delivery. Clear rules are required to prevent double counting of capacity and to define the relationship between FFR and other balancing or frequency-control services.

The aspects in this chapter are organized in the following structure:

- Preliminary stakeholder feedback indicates technical interest in providing FFR, particularly from BESS-based resources, while market feasibility, economic viability and regulatory clarity remain key implementation challenges. The preparedness of potential providers and other relevant stakeholders, together with the justification for their participation, is further addressed in Subchapter 4.3.1.
- Subchapter 4.3.2 presents an indicative procurement and auction design for FFR during the initial development phase of the service. It outlines the proposed auction structure, bid parameters, price formation, selection rules, partial acceptance, publication requirements and fallback procedures. The approach is adapted to the specific characteristics of FFR, including limited provider liquidity, control-area-based procurement, technical prequalification and the need to ensure locational and operational adequacy. The proposed framework should be understood as a development-phase concept that may be further refined following market consultation, regulatory assessment and operational experience.

4.4.1 Future FFR providers' and other stakeholders' preparedness and justification

The successful introduction of Fast Frequency Response (FFR) depends not only on a technically sound service specification, but also on the preparedness of potential providers and the wider stakeholder framework. Providers must be able to reserve power capacity and deliver the required active-power response, while the energy regulator, transmission system operator, market operator, aggregators, technology suppliers and other relevant parties must establish the operational, contractual and regulatory conditions for feasible and viable participation. The currently available Slovenian stakeholder input indicates a clear technical interest in FFR provision, but also identifies unresolved questions regarding market viability, procurement, capacity exclusivity, risk allocation and long-term economic justification.

Potential FFR providers may include power-generating modules, electricity storage modules, demand facilities, aggregators, inverter-based resources and electrical charging parks, if they meet the relevant technical and operational requirements. In the current concept, transmission-connected resources at 400 kV, 220 kV and 110 kV voltage level are considered the primary candidates because their response can be observed and validated at the point of common coupling and because their geo-electrical dispersion can be coordinated with the needs of the control area. Technical neutrality should be preserved; however, participation must remain conditional on demonstrated response speed, available power headroom, energy sufficiency, measurement quality, local control capability and successful prequalification testing.

Battery Energy Storage Systems (BESS) appear particularly well prepared for the proposed service. The stakeholder input identified BESS installations at several transmission-network nodes as a practical basis for FFR provision. Their bidirectional power capability, fast converter control and relatively small energy requirement for short activations make them technically suitable for the

service. Existing or planned BESS do not necessarily need to be dedicated exclusively to FFR; a portion of their power and energy capability may be reserved for FFR while the remaining capacity is used for different commercial operation at the electricity market. This multifunctional use is economically attractive, but it requires clear reservation rules to ensure that the contracted FFR capacity remains fully available when required.

From the provider perspective, technical preparedness requires more than sufficient installed power. The resource must maintain the necessary charging or discharging headroom, an adequate state-of-charge range, fast autonomous local activation and reliable measurement of local frequency. Central supervisory control remains important for monitoring availability, managing reservation limits and coordinating the portfolio, but the activation itself should not depend on time-critical central communication.

The energy requirement is expected to be modest compared with the required power capacity because FFR is a short-duration service. For example, only a small share of BESS energy capacity would be needed for an activation lasting approximately 30 seconds. The exact requirement nevertheless depends on the final FFR product definition when implemented in the real system and electricity market, particularly the holding time, deactivation logic and coordination with primary droop control and other reserves. Consequently, energy sufficiency should be verified for the full required response envelope rather than assumed from converter power alone. The short duration of power impulses may also significantly affect the battery degradation, although this should be confirmed through technology-specific assessment and operational data.

The preparedness of other provider categories is likely to be more heterogeneous. Power-park modules, fast controllable demand and charging infrastructure may all contribute, but their capability depends on the available operating margin, control architecture, process constraints and response repeatability. In the available stakeholder input, conventional demand-side actions were considered generally slower than the proposed FFR response and therefore less competitive for this specific product. This should not exclude advanced fast-acting demand technologies from future qualification, for example data centres; rather, the same performance-based criteria should apply to all technologies.

Before continuing to the market preparedness, we must emphasize again the importance of the TSO's role. The TSO has a central role in converting technical preparedness into an operational service. It must determine the required total and locational FFR capacity through system studies, define the prequalification and compliance tests, verify the availability of contracted resources, and coordinate FFR with emergency and restoration plans. The proposed concept, according to the nature of it, favours a geographically dispersed provider portfolio within the control area, because excessive concentration at a single node or provider may reduce resilience and stability of the system and create undesirable local effects. Simulation-based planning and testing are therefore required both for the total control-area requirement and for individual unit settings.

Note that the real-system demonstration also affects stakeholder preparedness. Testing in an actual transmission network would provide representative evidence, but it introduces risks related to system collapse, customer exposure, equipment stress and liability. A controlled islanded transition and/or isolated operation without significant demand reduces these risks but is less representative and may require an artificial balancing resource. Provider willingness to participate in demonstration tests is therefore conditional on a clear test protocol, defined operational responsibilities, appropriate risk allocation and wider TSO coordination.

Market preparedness is less mature than technical preparedness. A provider that reserves headroom for FFR incurs an opportunity cost because the same capacity cannot simultaneously be offered without restriction in other balancing or commercial activities. Clear rules are therefore required to prevent double counting and to define the relationship between FFR and existing services such as FCR, aFRR and mFRR. Under the proposed concept, FFR is primarily an availability product: its system value is created by the assured presence of fast active-power capability during rare but potentially severe events, rather than by frequent energy delivery. This supports a remuneration model with a capacity-payment component, complemented where appropriate by activation and performance provisions.

For the initial development phase, closed a-priori agreements between the TSO and qualified providers offer a pragmatic implementation route. Annual or multi-year contracts can provide investment certainty, simplify testing and avoid creating a thin or illiquid bidding market before sufficient provider participation exists. The current concept therefore favours procurement within one control area, without exchange or sharing during the development phase, while local competitive bidding mechanisms may be explored after the technical need, provider base and compliance framework are better established. This should be understood as a staged first wave-boost market-development approach rather than a permanent restriction on future market design.

Although beyond the scope of this task, an indicative annualized value of at least 65.000 EUR /MW/year was proposed by some of the stakeholders as a rough reference for FFR capacity procurement. This estimate is useful as preliminary stakeholder evidence, but it is not a final market price. It excludes discounting, inflation, technology degradation, financing structure, additional control and communication costs, opportunity costs, and revenues from other services. A robust pricing methodology should therefore combine investment and operating costs with the opportunity cost of reserved capacity, the required availability level, performance risk, contract duration and the system value of avoided frequency-security consequences.

Overall, the present assessment indicates that technical willingness and capability are emerging, particularly among BESS-based providers, while market and regulatory readiness remain conditional. A more competitive market design may follow once sufficient operational evidence, provider diversity and regulatory clarity have been established.

Stakeholder analysis note: This assessment reflects the currently available TwinEU project material and limited stakeholder input from Slovenia. It should not be interpreted as a complete consultation of all European market participants or technology providers or as a final regulatory or pricing proposal. Wider consultation with the TSOs, regulators, market operators and participants remains necessary.

4.4.2 Indicative procurement and auction design for FFR

For the provision of the indicative procurement and auction design for FFR, we must once again emphasize the basic guidelines of this aspect. Namely, in the introduction of the market and pricing aspects' chapter, as well as in the stakeholder analysis, we already established that FFR is procured for the specific dynamic-security needs of a control area and the number of qualified providers may initially be limited. Thus, a closed, ex ante procurement procedure is considered appropriate for the development phase. The procedure should be organized by the transmission system operator (TSO) and limited to prequalified providers located within the relevant control area. Neither exchange nor sharing of FFR between control areas is envisaged at this stage. Annual or multi-year contracts can provide stable availability and investment certainty, while a local competitive bidding market may be

introduced once sufficient provider diversity, liquidity and operational experience have been established.

The proposed procurement concept builds on a two-round auction procedure. Its purpose is to preserve transparent price formation while allowing providers to improve their commercial offers without changing the prequalified technical characteristics of the service. The procedure should remain technology-neutral and non-discriminatory, while recognizing that FFR has local operational influence and that the selected portfolio may therefore need to satisfy predefined locational, dispersion and system-security constraints.

4.4.2.1 Indicative auction procedure

The auction may consist of an initial round and a final round and may be conducted under the supervision of a notary or another independent observer, where required by the applicable procurement framework. In each round, the TSO should open and validate the submitted bids, exclude bids that do not comply with the auction rules, and determine the technically feasible and economically most advantageous bid portfolio.

At the end of each round, the TSO should disclose an anonymized summary of the leading bids, including the offered FFR capacity, the reservation price, the activation energy price where applicable, and the resulting total reservation value. Disclosure should remain consistent with confidentiality, competition and procurement requirements.

The exact start and end of the final round should be formally announced by the auction supervisor. An indicative duration of 15 minutes may be applied. Bids submitted outside the formally defined auction period should be considered invalid.

Before the auction begins, the TSO should formally approve and securely record the maximum acceptable reservation price and, where activation energy is remunerated separately, the maximum acceptable activation energy price. For an in-person auction, these caps may be deposited in sealed form with the supervising notary or independent observer.

Bid prices should be fixed, expressed in EUR and not linked to an index during the relevant contract period unless indexation is explicitly specified in the procurement documentation. Incorrectly completed or incomplete bids should be considered invalid.

Each provider should submit no more than one non-exclusive bid for the same prequalified unit or portfolio. Where a provider wishes to express quantity-dependent pricing, it may submit up to three bids for the same unit or portfolio, provided that these bids are clearly identified as mutually exclusive.

In the final round, providers should be permitted to resubmit only the bids submitted in the initial round. The offered capacity, direction, point of common coupling and technical parameters should remain unchanged. Only the reservation price and, where applicable, the activation energy price may be reduced or retained at the initial-round level.

Where a final-round bid does not comply with these requirements, the corresponding initial-round bid should remain valid. If an authorised representative does not participate in the final round or does not submit a revised bid, the initial-round bid should also remain valid.

Furthermore, the TSO should first identify a technically feasible portfolio that satisfies the required total FFR capacity, prequalification limits, product direction, geo-electrical dispersion and any predefined system-level or local constraints. Price ranking should be applied only within the set of

technically feasible solutions; a purely price-based ranking should not override operational-security requirements.

Within a technically feasible portfolio, priority should be given to bids with the lower reservation price. Where reservation prices are equal, the bid with the lower activation energy price should take priority. If both prices are equal, the earlier valid time stamp may be used as the final tie-breaker. Unless otherwise specified, accepted providers should be remunerated according to their offered prices.

The marginal accepted bid may be accepted in full or only for the quantity required to reach the total procured capacity, provided that the accepted quantity is not below the applicable minimum bid quantity and does not exceed the provider's prequalified capability. Where partial acceptance of the marginal bid is not feasible, the TSO may re-optimize the quantities of other accepted bids within the published auction rules.

The auction may be fully or partially successful. A partial result may be accepted where the procured quantity is lower than the target quantity but still provides justified system value. Any remaining capacity requirement should be addressed through a predefined fallback procedure.

The TSO should publish an anonymized list of accepted bids within a predefined period, indicatively no later than two working days after the auction. The published information should include the accepted capacity, reservation price, activation energy price where applicable, FFR direction and contract period, subject to confidentiality requirements.

The TSO may reserve the right to conduct a subsequent negotiation procedure where the auction is unsuccessful because the submitted prices exceed the predefined caps or because insufficient capacity is offered. The conditions for such negotiations should be announced in advance and applied transparently and non-discriminatorily.

FFR remuneration should primarily compensate for the continuous reservation and verified availability of the contracted capacity. A separate activation energy payment may be used, although the delivered energy volume is expected to be limited because of the short activation duration. The contract should also define availability monitoring, performance verification, non-delivery penalties and rules preventing the same capacity from being counted simultaneously for incompatible services.

Disclaimer: The proposed auction design is an indicative development-phase concept rather than a final procurement specification. Its implementation would require alignment with the applicable national procurement framework, electricity-market rules, regulatory approval, the final FFR product definition and the results of stakeholder consultation.

The indicative bid characteristics are shown in the following table:

Table 4-3 – Indicative bid characteristics

Bid parameter	Indicative FFR-specific requirement
Offered FFR capacity	MW. The permitted decimal resolution should be defined by the TSO and should not unnecessarily exclude smaller resources or aggregated portfolios.
FFR direction or product	Upward, downward or symmetric FFR, as defined in the procurement documentation.
Reservation price	EUR/MW/h, rounded to two decimal places, or an equivalent annual or contract-period capacity price.
Activation energy price	EUR/MWh, rounded to two decimal places, where activation energy is settled separately.
Separate start-up price	Not proposed. FFR is activated automatically according to the defined frequency characteristic and does not require a separately instructed start.
Number of bids	One non-exclusive bid per prequalified unit or portfolio. Up to three mutually exclusive bids may be submitted where the price depends on the accepted quantity.
Minimum bid quantity	To be defined by the TSO. It should be sufficiently low to support technology neutrality, aggregation and adequate market participation. A proposal of 5 MW was given.
Maximum bid quantity	Limited to the FFR capacity recognized through prequalification for the relevant unit or portfolio.
Minimum quantity increment	Indicatively 1 MW or a lower increment where justified by the expected provider structure.
Maximum acceptable prices	Reservation and activation energy prices, where applicable, may be capped in the bid-selection procedure.
Contract period	Annual or multi-year procurement is preferred during the initial development phase.
Technical and locational data	The prequalified response parameters, point of common coupling, provider category and any applicable locational classification must be identified and remain unchanged during the auction.

4.5 Summary of the technical and system criteria regarding the FFR service

This section summarises the main technical and system-level criteria proposed for the FFR service. The requirements define how FFR should be activated, delivered, sustained, measured and coordinated within the control area. They also provide a common basis for provider qualification,

system planning and future market implementation. The key parameters and high-level service characteristics are presented in the following two tables:

Table 4-4 - FFR technical requirement summary

Fast Frequency Response (FFR) - technical requirements				
Activation	Continuous in all of the system states depending on the current frequency deviation nadir (outside of +/- 200 mHz)			
System and equipment time delay of activation (no intentional delay)	0 ms - 100 ms	t1	t2	t3
Rise time to a full 100% activation	200 ms - 400 ms			
Full activation sustainability	2 s - 30 s			
Decline time after a full activation	no more than 30 s, depending on the primary reserve activation			
Frequency sampling resolution	20 ms			
Point of common coupling	Transmission-connected (400, 220, 110 kV)			

Table 4-5 - High-level overview of the FFR service

Fast Frequency Response (FFR) - high-level overview	
What is FFR?	FFR is a frequency control expressed as very fast active power response to a frequency deviation
What frequency?	Filtered local frequency at the Point of Common Coupling (PCC) Frequency sampling resolution of no more than 20 ms
Who/What?	Qualified transmission-connected providers: electricity storage modules, power park modules, demand facilities, electrical charging parks etc. *Transmission-connection is considered a high-voltage PCC at 400, 220 and 110 kV
When?	Provision of FFR capacity: All the time in the states of interest as a reserved active power capacity of the FFR provider. Activation of FFR: Depending on the frequency deviation - start of activation at +/- 200 mHz, at least linear adaptation beyond, full activation at +/- 800 mHz.
Unit provision of FFR [pu]	- In the case of multifunctional use of the unit: Must be limited to a certain degree of the nominal active of the power unit in order to achieve geo-electrical dispersion of the FFR service providers. Minimum is 0.05 pu, preferred is 0.16 pu, upper limit is 0.32 pu. Larger unit provision of FFR is not recommended due to the dispersion of the total area FFR. - In the case of exclusive singular FFR use of the unit: Limited to the techno-economic feasibility and viability The providers and the TSO must test FFR unit setting and activation in order to analyse the stability of the system.
Total regulation area (nodal) FFR [MW or pu]	Based on the simulation of islanded and/or transition to/out of islanded operation of the whole or parts of the regulation area considering H_{min} or annual percentile of available H , available FCR, active power imbalance, frequency nadir (maximum steady-state frequency deviation) which are specific of the considered system. It is strongly recommended that the TSO simulates the activation of FFR to analyse the stability of the system.
Market:	The service should be limited to a single regulation area. Neither exchange nor sharing between regulation areas is permitted. Closed, ex ante annual agreements are encouraged during the development phase of the new FFR service to avoid adversely affecting market liquidity. Local bidding markets may be explored at a later stage.
Classification of FFR	Non-mandatory, depending on the system topology and level of control of the TSO. Classification can be based on: Voltage level: Group I (400, 220 kV, i.e. System level) & Group II (110 kV, i.e.. Local level) and/or Mode of operation: Grid-forming (faster FFR due to omitted PLL delay) & Grid-following (slower FFR, but much faster than the FCR).

5 Simulations of the FFR service

This chapter presents the simulation-based assessment of the proposed FFR service and its impact on the frequency response of the Slovenian and the wider Continental electric power system. The analyses are performed in the Wide European Network Dynamics (WENDY) simulation environment, developed by EIMV [40] in DigSILENT PowerFactory [41]. WENDY is a highly detailed, multipurpose dynamic model designed to provide realistic responses of the electric power system under different operating conditions and disturbances.

The chapter first describes the electric power system model and the implementation of the FFR control in the simulation environment. The proposed service is then assessed through representative scenarios, including the operation of the interconnected Slovenian control area during a European system split, islanding and isolated operation of the Slovenian control area, the Severna Primorska loop, the Drava river power plant chain, and a real-system islanding incident recorded in 2026.

The simulations provide a hard solid demonstration of the importance of FFR development and implementation. The chapter concludes with a summary of the main findings and a justification for using simulation-based validation instead of deliberate real-system disturbance testing.

Important note:

The WENDY simulation environment, along with the DSA tools, demonstrating the FFR concept, is a key enabling asset of the Slovenian TwinEU pilot, as it translates the project objectives of improved system observability, controllability and stability management into a detailed simulation-based assessment framework. Its comprehensive dynamic representation enables the FFR concept to be evaluated under realistic operating conditions and severe disturbances that cannot be safely reproduced in the actual power system. By covering both system-wide and local scenarios, WENDY provides the technical evidence required to quantify the impact of FFR, define appropriate service parameters and support its future planning and implementation. In this respect, WENDY provides a practical digital-twin-oriented bridge between conceptual development, demonstration and future operational deployment, thereby strengthening the replicability and wider European relevance of the TwinEU results.

5.1 Simulation model of the electric power system

To obtain somewhat authentic results, an appropriate tool must be used. The simulation results that follow are produced using a state-of-the-art dynamic simulation model that contains most of the European interconnection. It is built from separate interconnected networks that represent each of the ENTSO-E zones. These include the transmission network of each zone and the power plants that are connected to the modelled voltage levels, as well as the dispersed production, FACTS devices, etc.

The scope of the model is shown by the figures below.

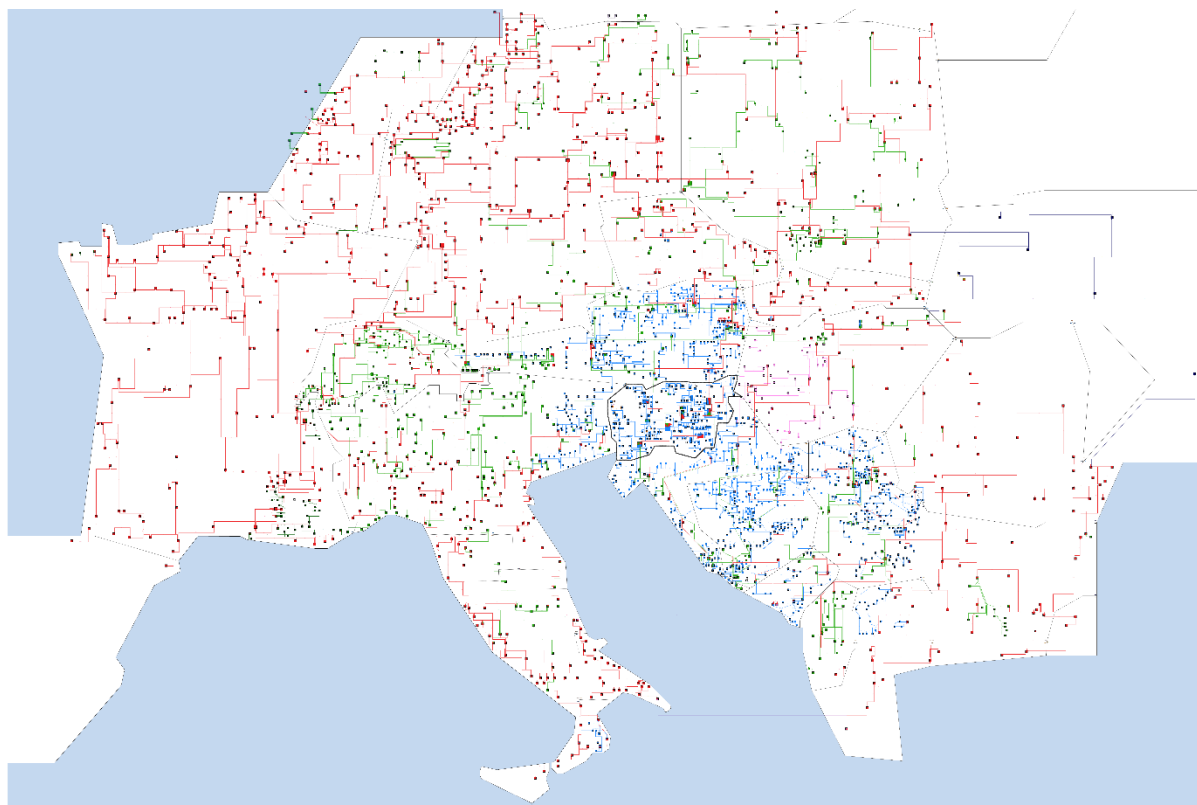


Figure 5-1: General scope of the simulation model

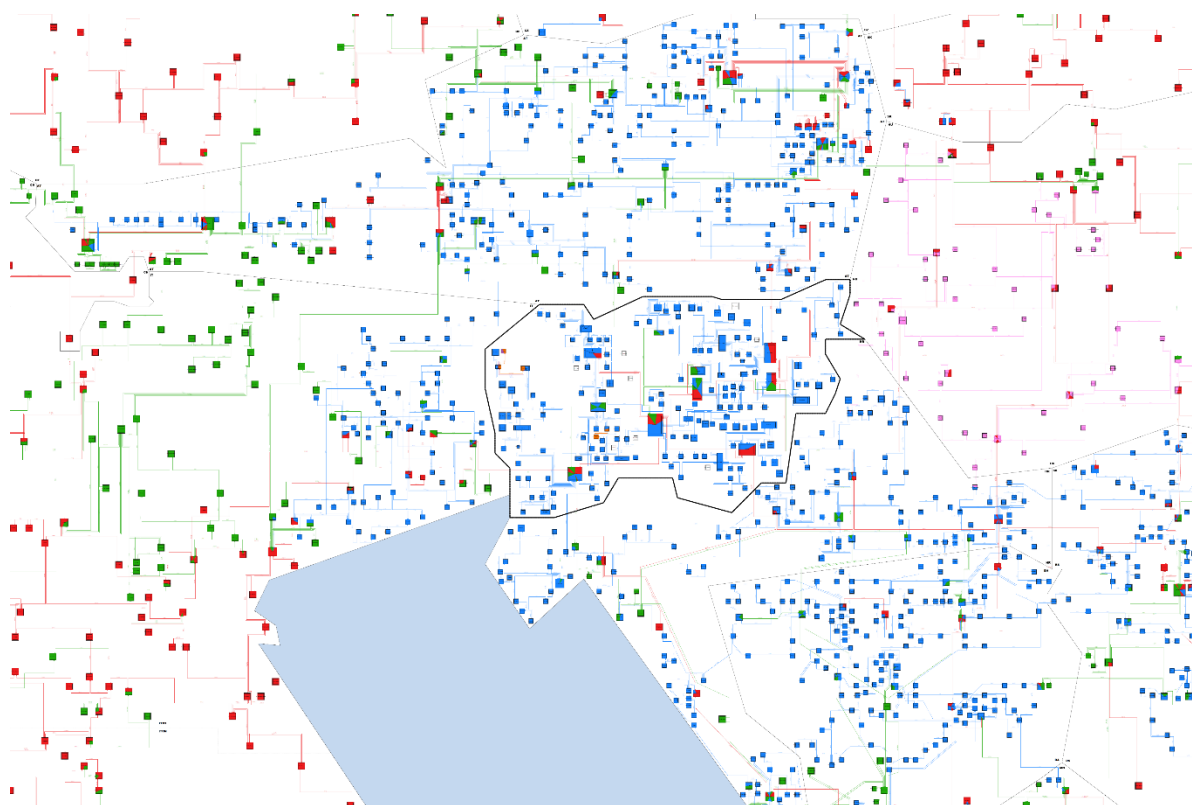


Figure 5-2: Focus on the Slovenian model

The simulation model is made in DiGSILENT PowerFactory.

Regionally, the network model has the following contents:

ENTSO-E Zone	Region/State	Level of modelling
AL00	Albania	Entire 220 kV and 400 kV network
AT00	Austria	Entire 110, 220 and 400 kV network
BA00	Bosnia	Entire 110 kV, 220 kV and 400 kV network
BE00	Belgium	Entire 400 kV network
BG00	Bulgaria	Entire 400 kV network, partial 220 kV
CH00	Switzerland	Entire 220 kV and 400 kV network
CZ00	Czechia	Entire 220 kV and 400 kV network
DE00	Germany	Entire 400 kV network, partial 220 kV
DK00	Denmark	Edge area
ES00	Spain	Edge area
FR00	France	Entire 400 kV network, partial 220 kV
GR00	Greece	Partial 400 kV network
HR00	Croatia	Entire 110, 220 and 400 kV network
HU00	Hungary	Entire 220 kV and 400 kV network, partial 110 kV
ITCA	IT, Calabria	Entire 220 kV and 400 kV network
ITCN	IT, central north	Entire 220 kV and 400 kV network
ITCS	IT, central south	Entire 220 kV and 400 kV network
ITN1	IT, north	Entire 220 kV and 400 kV network, partial 110 kV
ITS1	IT, south	Entire 220 kV and 400 kV network
ITSI	IT, Sicily	Edge area
LT00	Lithuania	Partial 400 kV network
MK00	Macedonia	Entire 400 kV network and partial 110 kV
MN00	Montenegro	Entire 110, 220 and 400 kV network
NL00	Netherlands	Entire 400 kV and partial 220 kV network
NO00	Norway	Edge area
PL00	Poland	Entire 220 kV and 400 kV network
RO00	Romania	Entire 400 kV network, partial 220 kV
RS00	Serbia	Entire 220 kV and 400 kV network
SE00	Sweden	Partial 400 kV network
SI00	Slovenia	Entire 110, 220 and 400 kV network
SK00	Slovakia	Entire 220 kV and 400 kV network
TR00	Turkey	Edge area
UA00	Ukraine	Partial 400 kV, 330 kV and 750 kV network

The edge areas represent radially connected parts of the network that are further unmodelled due to no expected increase in accuracy of the model.

Specifically, the scope of the model can be given with the metrics below:

Table 5-1: Scope of electrical power system simulation model

Element name	# of
Grid zone	33
Site (transformer station)	2392
Substation	2960
Busbar	5876
Terminal (node)	73367
Line	4355
Transformer	2081
Static generator	4336
Synchronous machine	1168
Composite model (dynamics)	1097

As such, the simulation model possesses a mass of elements that is deemed sufficient to produce realistic results. The data used for model parameters was either obtained from publicly available sources or was produced from our archive, and it is coordinated with the model used in the Task 6.7 – however, the level of the details is much higher due to the nature, needs and purpose of the FFR.

5.2 Modelling of the FFR in the simulation environment

FFR's activation algorithm and dynamic response are modelled with the set of parameters and formulation put forth in the fourth chapter. Specifically, in the PowerFactory software, the service is realised by using a battery storage system that uses the following characteristics to achieve simplicity of simulation:

1. The battery storage system (generator) is constantly connected to the transmission network.
2. The generator model does not have any short-circuit contribution, nor is it capable of producing any reactive power.
3. The generator setpoint is always 0 MW at steady state.
4. The generator only ever produces active power for FFR purposes as a response to changes in frequency and is never engaged otherwise.

The transfer function of the algorithm is largely non-linear and is realised with the inbuilt DSL language of the PowerFactory software (Figure 5-3).

The most important characteristics of the control scheme are:

1. A continuous deadband that ignores any changes in frequency between 50,2 and 49,8 Hz but applies an input to the transfer function outside of that deadband continuously
2. A limited frequency response that ignores any changes in frequency larger than 0,8 Hz in each direction from 50 Hz.
3. A droop that ensures that the function achieves full response when the frequency is higher than 50,8 Hz or lower than 49,2 Hz.

4. A filtered frequency input and active power output to achieve sufficient delay of response, as prescribed in Chapter 4.1.1.

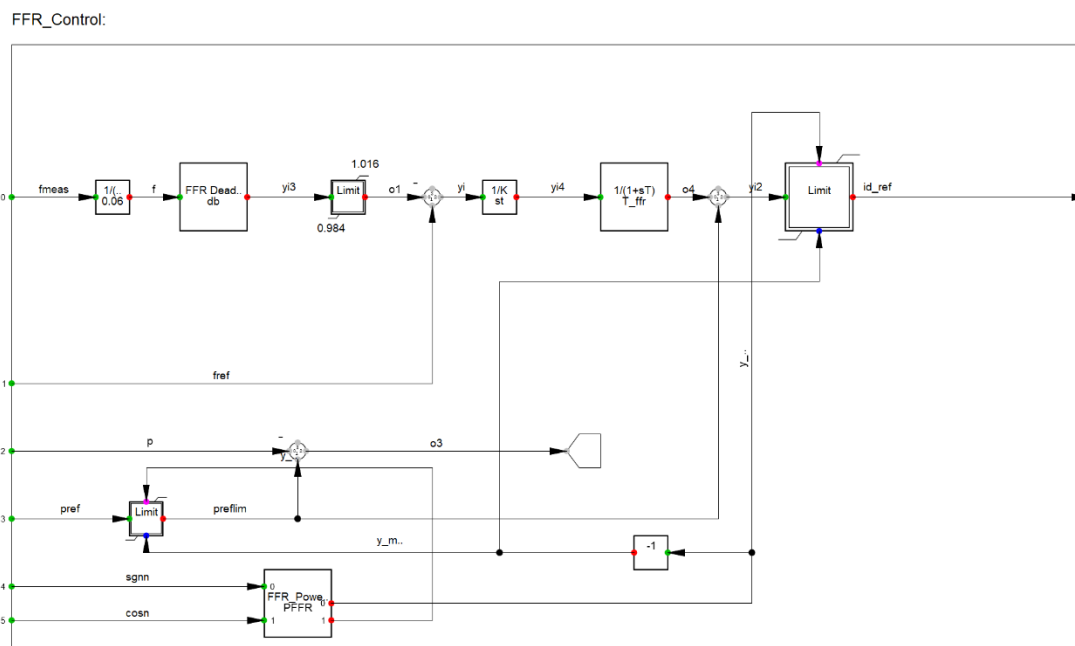


Figure 5-3: FFR control scheme

The algorithm is tested in a limited and controlled simulation environment with a frequency controlled voltage source to quickly observe, if it behaves as expected:

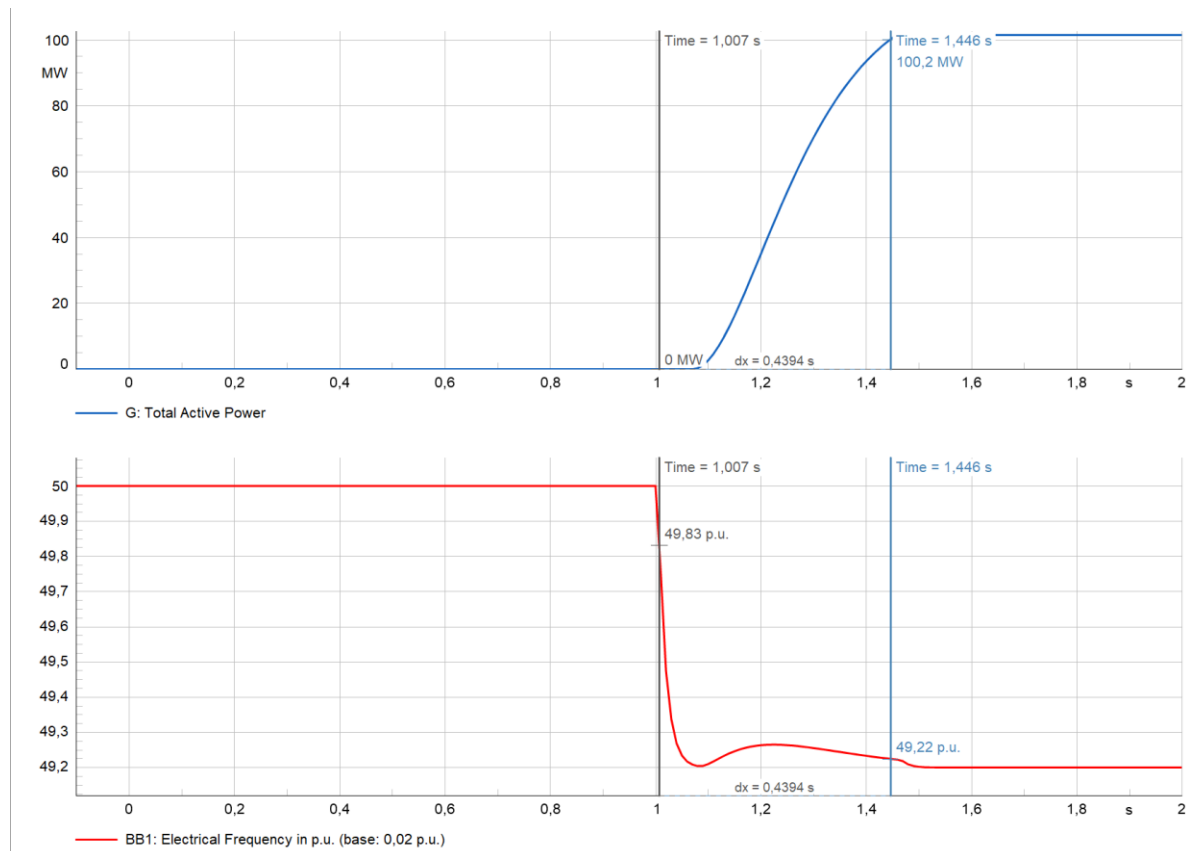


Figure 5-4: Response of the FFR algorithm in a controlled simulation environment

As observed, the algorithm ensures approximately 100 % of response (here chosen to be 100 MW) around 0,5 seconds after the frequency drop to 49,2 Hz occurs.

5.3 Simulation scenarios and key results

The proposed FFR algorithm is tested in a scenario where there is a moderate amount of synchronous production (actual, real inertia) in the system. The scenario also includes significant active power transit from the north to the south of the simulated power system, which becomes important later on.

5.3.1 Interconnected control area of Slovenia during the European system split

The first simulated disturbance is not exactly realistic, but it was chosen as a good example of how FFR could display its influence on changing frequency. The simulated power system is split across the following borders:

- France/Italy,
- Switzerland/Italy,
- Austria/Italy,
- Austria/Hungary,
- Austria/Slovenia
- Slovakia/Hungary,
- Ukraine/Hungary

The system split is graphically shown in Figure 5-5.

In the rest of the split interconnection, there are 10 more sources of 320 MW each, situated at major 400 or 220 kV nodes in each of the following network zones:

1. North Italy (ITN1)
2. Croatia (HR00)
3. Bosnia (BA00)
4. Montenegro (ME00)
5. Albania (AL00)
6. Macedonia (MK00)
7. Serbia (RS00)
8. Hungary (HU00)
9. Romania (RO00)
10. Bulgaria (BG00)

As the system split occurs, a sudden deficit of about 5500 MW in the southern split region prompts a rapid decline of frequency.

The simulated installed FFR capacity in Slovenia is 320 MW, realised with 10 sources of 32 MW each that are situated in major 110 kV nodes across the Slovenian transmission network.

A simulation is performed with and without FFR generators to determine the difference in frequency response of the split system.

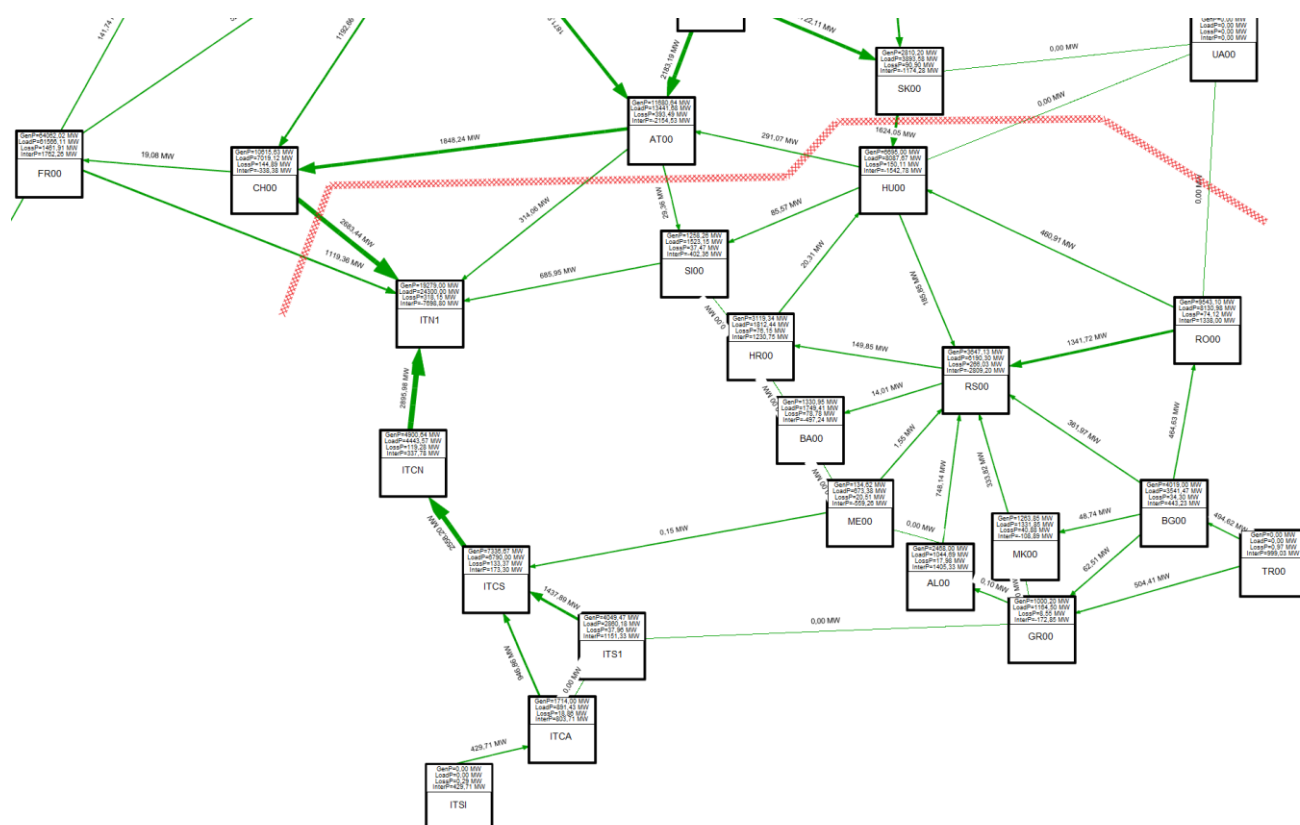


Figure 5-5: Schematic of the system split

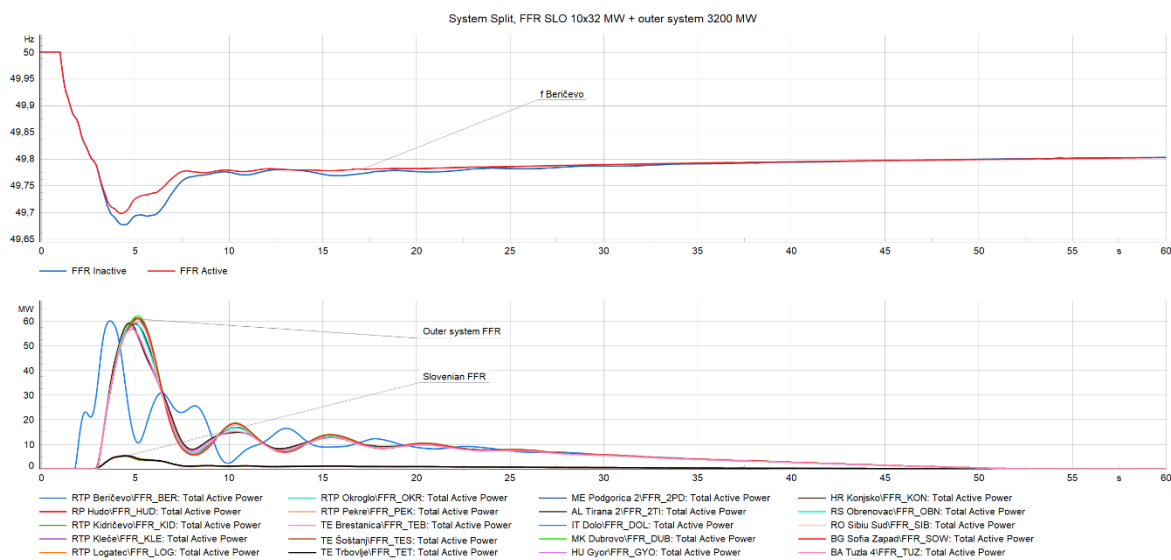


Figure 5-6: Outcome of a system split and FFR function

There is a small, but distinct difference between the frequency responses of the simulated system when FFR is enabled or disabled. The difference between the two nadirs is around 50 mHz. The disconnected transit of 5500 MW is not very imposing to the mass of synchronous production still connected in the split part of the system, but it is enough to showcase the response of a cumulative 3520 MW of FFR.

We can view the separate response of different parts of the system if we display the frequency of each network zone with a different graph:

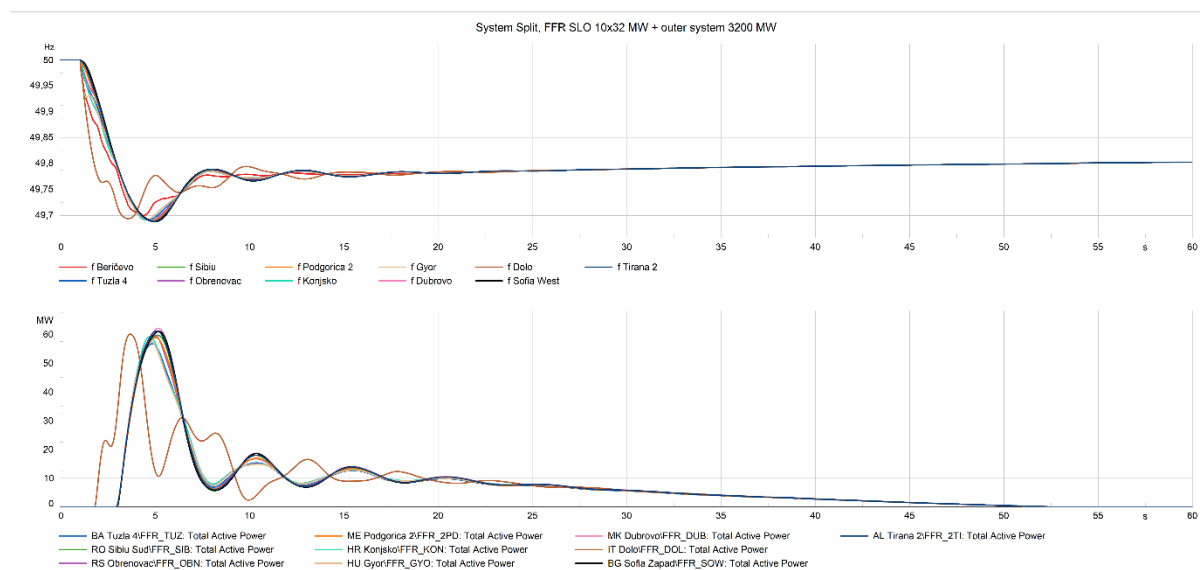


Figure 5-7: Frequency responses of different network zones

We can observe that the greatest RoCoF occurs in northern Italy, where the largest production deficit occurs in the moment of the system split. Thus, the FFR activation is earliest there. A similarly large frequency gradient occurs in Slovenia too, but the threshold of 49,8 Hz is achieved almost at the same time as elsewhere in the system.

5.3.2 Slovenian control area islanding and isolated operation

A more contrasted display of FFR's effect can be observed if we form a system split around the border of the Slovenian power system. This demands disconnecting all of the 15 power lines that connect Slovenia to the surrounding transmission network, which makes this event highly unlikely, but gives us the opportunity to observe the effect of FFR within an isolated network.

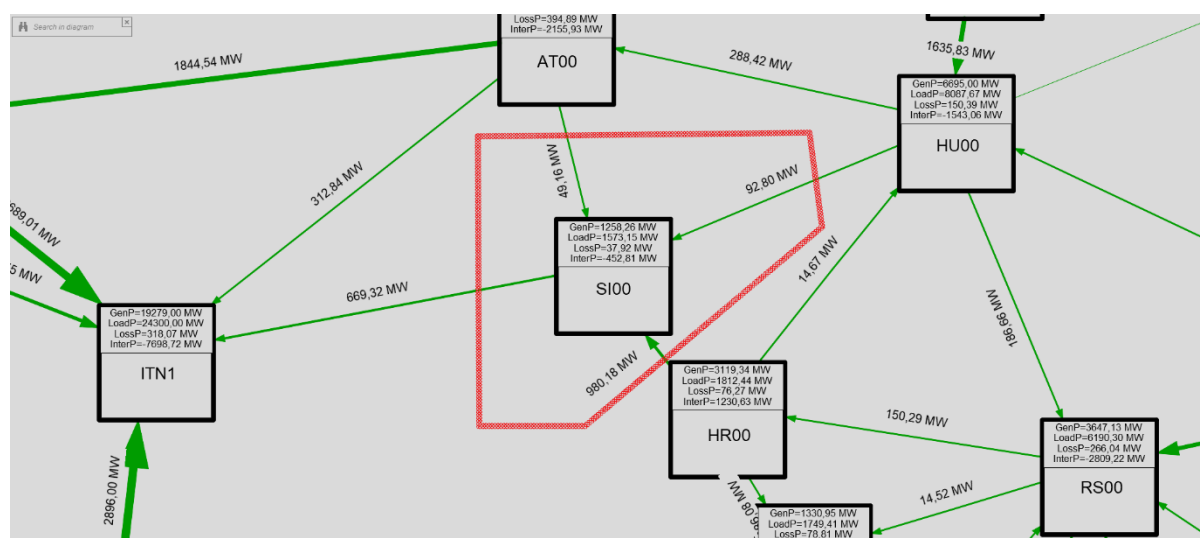


Figure 5-8: Steady state before the islanding of Slovenia

Before the external interconnection is split from the Slovenian network, there is about 450 MW of negative balance that causes the frequency to drop on disconnect.

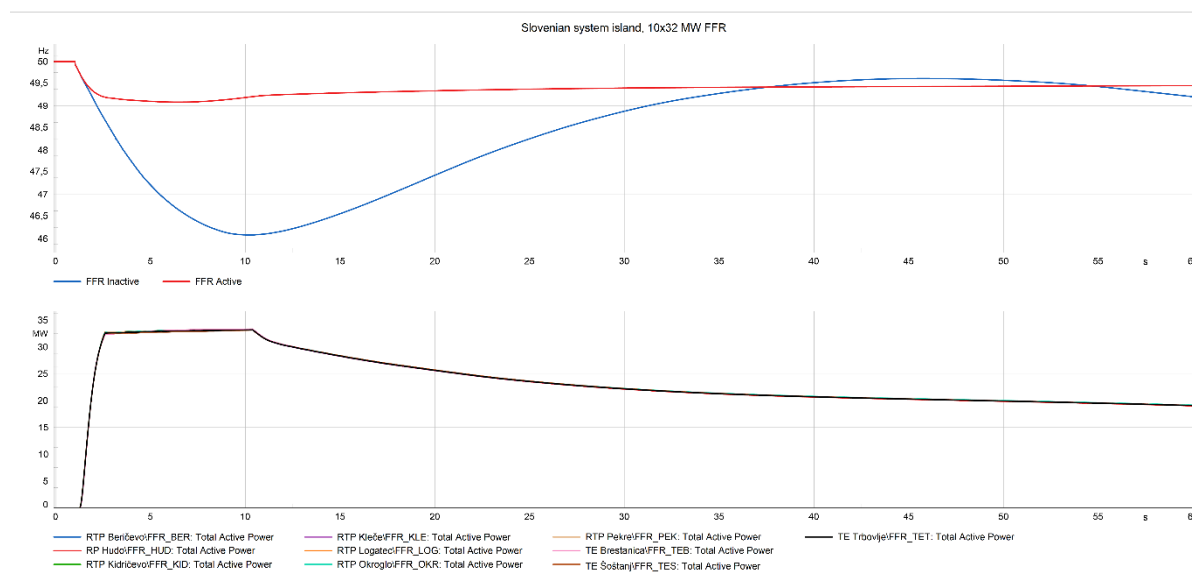


Figure 5-9: FFR function in the islanded Slovenian network

In this case, we can observe the frequency dropping below the saturation of the FFR's power range. The FFR activates fully within approximately a second after the disconnection event and stays at full power until the frequency climbs above 49.2 Hz, after which it gradually decreases its output as turbine governors take care of the deficit.

To compare the different outcomes more in detail, we add another simulation scenario, where the FFR range is only 16 MW, which corresponds to the primary frequency reserve in Slovenia.

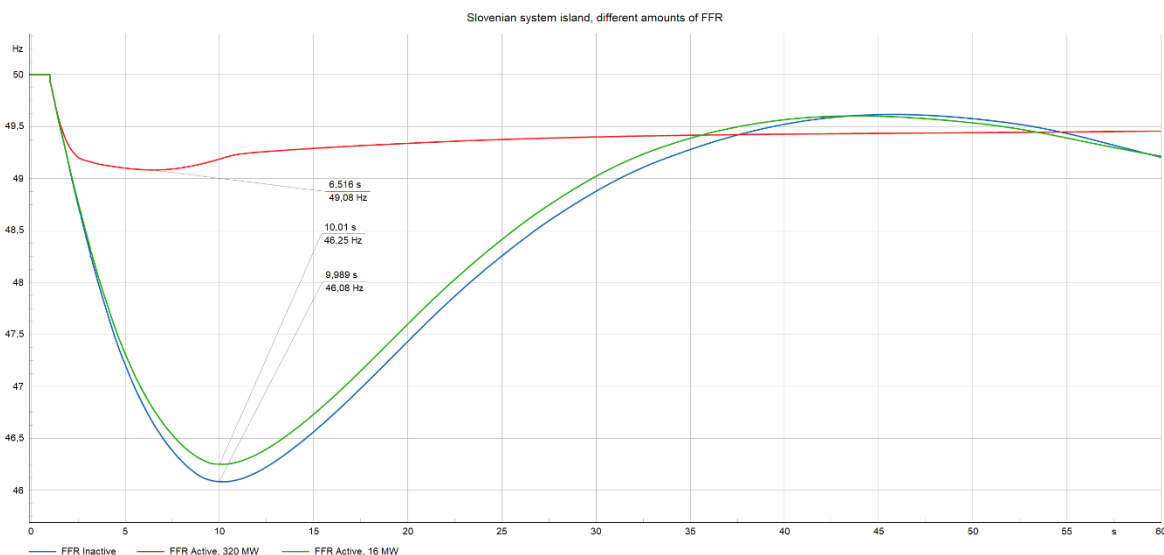


Figure 5-10: Different nadirs with different amounts of FFR

In this comparison, we can see how 16 MW of FFR barely improves the response, whereas the proposed amount of 320 MW convincingly aids the frequency response. The difference in nadirs between full FFR capacity or none is approximately 3 Hz.

5.3.3 The Severnoprimska loop

The northern Primorska region of Slovenia is characterized by having a distinctive loop of 110 kV transmission network that used to be connected into the rest of the Slovenian network by a double power line that runs a single corridor.

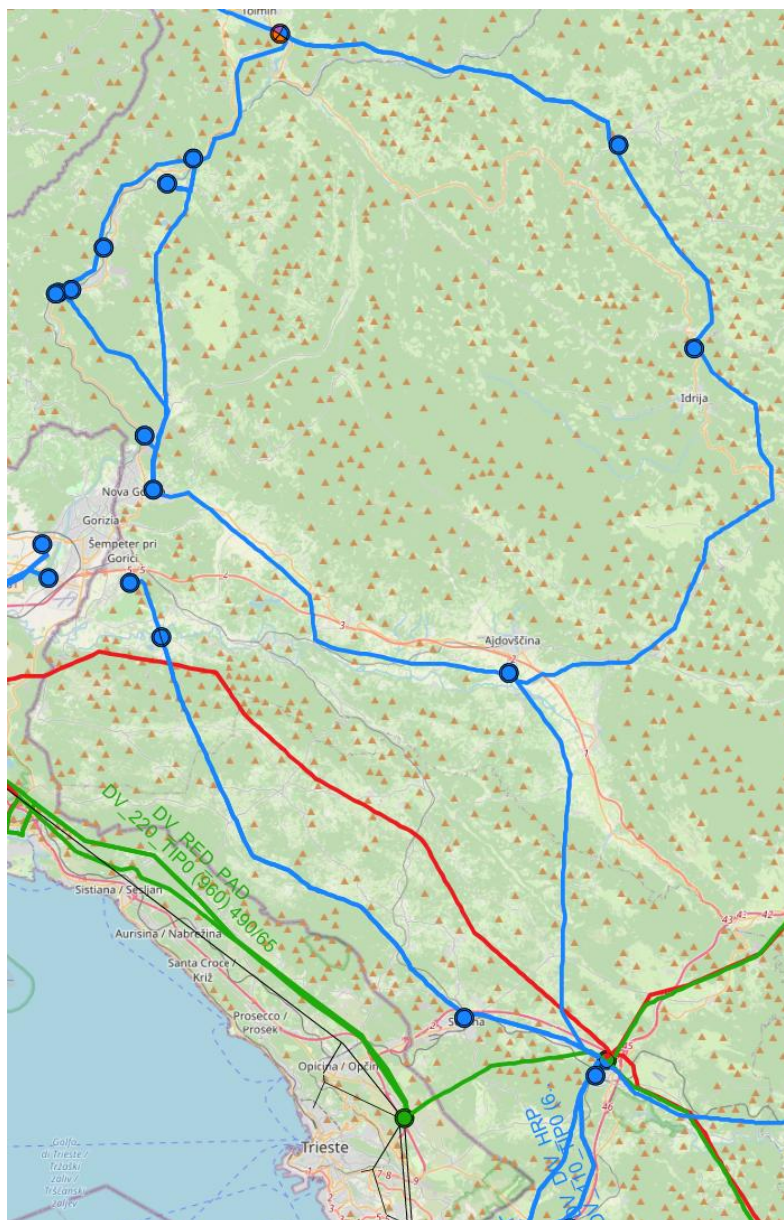


Figure 5-11: The Severnoprimska 110 kV loop with the single corridor interconnection visible

This part of the Slovenian network is now interconnected via two additional power lines, but the past configuration made it very prone to stability issues and relatively frequent isolated operations. This testing scenario thus proposes a more realistic way of a system split for FFR estimation.

We set the simulation so that the single corridor double line disconnects 1 second after steady-state. The PSHPP Avče is in pumping mode at 100 MW. Together with the power demand in the isolated network, it causes the frequency to start dropping. We simulate the event with a single 32 MW source of FFR situated in the Nova Gorica substation.

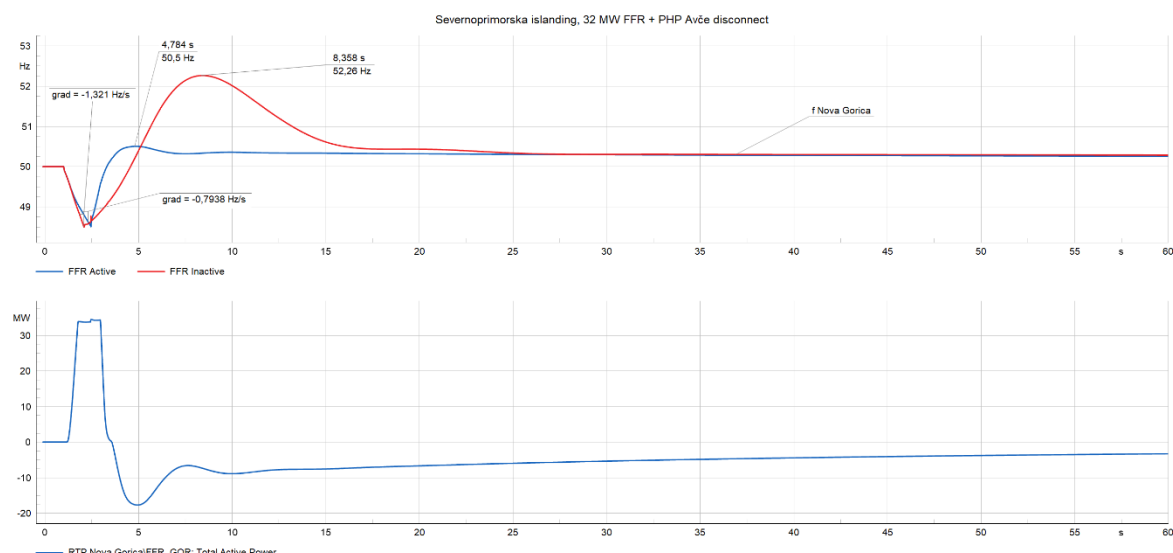


Figure 5-12: Severnoprimsorska islanding with FFR

Normally, PSHPP Avče is tied to the single corridor line state, so that it disconnects immediately, should the network loop become isolated. But for the purpose of this experiment, we leave it connected with a threshold of 48.5 Hz, after which it switches off. This causes a subsequent rise in frequency.

We can firstly observe that the inclusion of FFR approximately halves the RoCoF after the line outage event. It also lessens the nadir of the following overfrequency to just 50.5 Hz, compared to the value of 52.26 MW in the case that FFR is inactive. The entire transient duration is significantly shortened.

5.3.4 Drava river power plant chain islanding and isolated operation

We can demonstrate the effect of FFR in an even smaller electrical island by applying the system split to only affect the Drava hydroelectric plants.

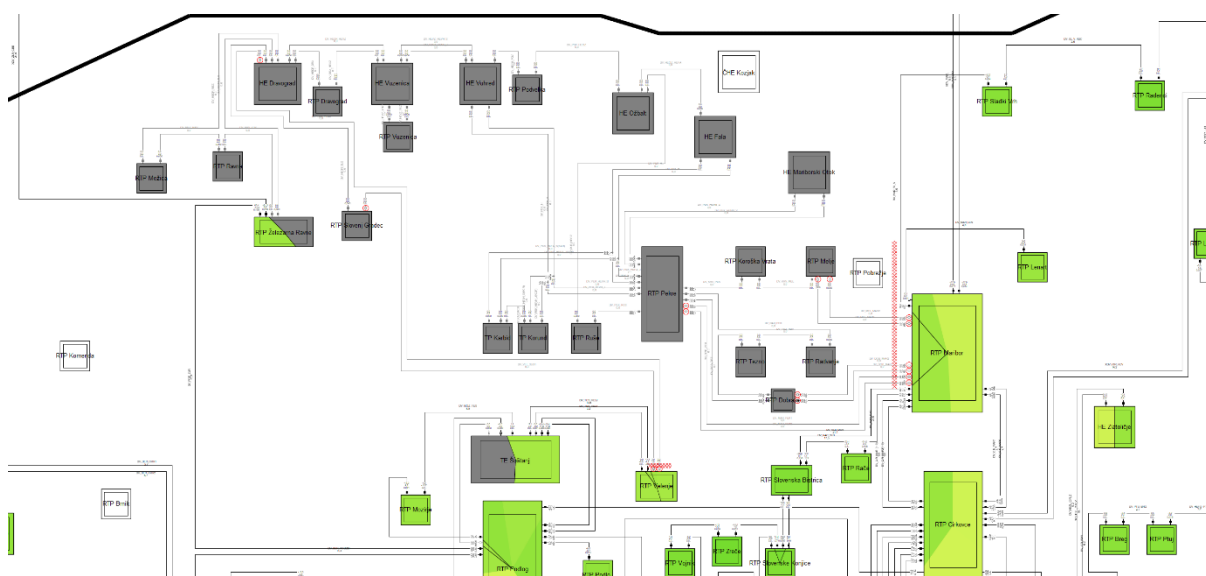


Figure 5-13: Islanding scheme of the Drava hydro chain

For a more realistic (for a lack of a better descriptor) and manageable model scenario, we only split the upper plant chain from the system, while the two larger plants remain connected to the system. The split is illustrated by Figure 5-13.

When the hydro chain is isolated from the system, it remains connected with the FFR generator situated in the Pekre substation.

Before the islanding, the hydro chain is operating at 150 MW out of the total 345 MW of installed power. The surplus causes the frequency to rise sharply after the disconnection. Soon after the transient passes, an additional load of 50 MW is connected in the Ruše substation to cause a drop in frequency, displaying the dual range capability of the FFR algorithm.

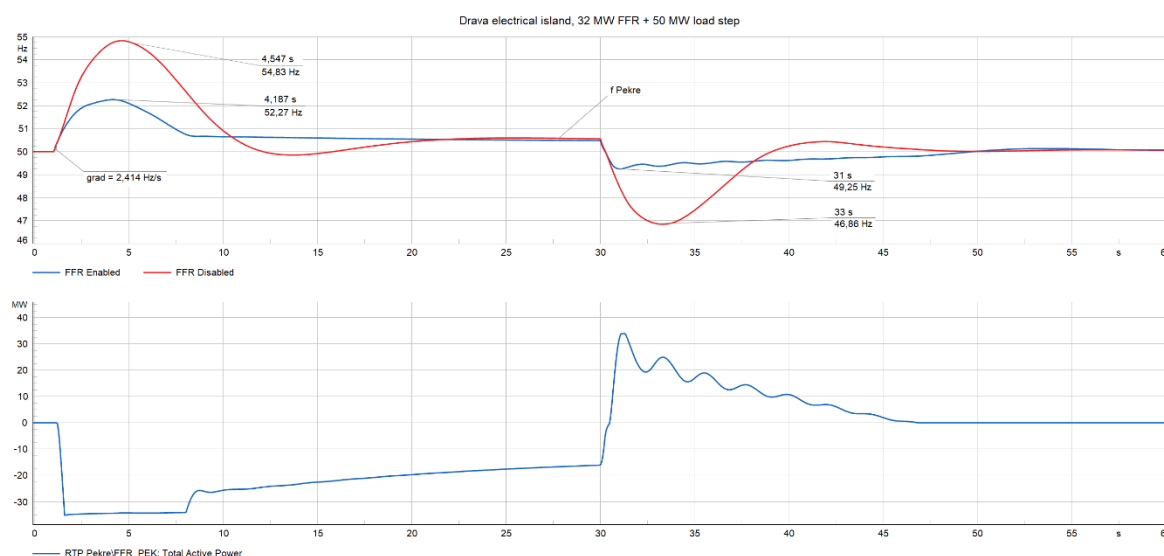


Figure 5-14: Islanding event of the Drava hydropower chain

As the disconnect happens, the frequency spikes as a consequence of power surplus in the islanded region of the network. The FFR goes into the negative power range, absorbing the surplus and helping stabilize the frequency sooner. The difference in nadir is around 2.5 Hz.

The opposite can be observed in the contrasting case, when an additional load that suddenly connects creates a dip in frequency. The FFR quickly switches from negative to positive power contribution, decreasing the resulting nadir by about 2.4 Hz. When the frequency reaches stable values around 50 Hz, the FFR smoothly switches off, as displayed by the flat power graph soon after the 45-second mark.

5.3.5 Real system islanding incident and isolated operation in 2026

On 20th of February 2026, an islanding incident occurred in a part of the transmission systems of Slovenia and Croatia. The incident resulted from an extreme weather event, with the following proximate factors:

1. Most 400 kilovolt power lines connected to one of the biggest substations in Slovenia were offline due to a fault
2. A large part of the northeastern transmission network in Slovenia was weakly connected due to faults and disconnections of multiple 110 kV lines
3. A large part of the bordering Croatian transmission network was operating on separated busbars in one of the principal substations

As a result of the combination above, several power lines overloaded and tripped, leaving a large part of the shared SI/HR transmission network (19 substations and two hydropower plants) in islanded operation.

The frequency dipped to a nadir of 46.7 Hz with an initial RoCoF of -4.3 Hz/s (calculated with a 500 ms sliding window). The frequency recovery lasted for several minutes and after settling, the island was resynchronized to the interconnection.

Disclaimer: The visual representation of the formed island was omitted from the final version of the deliverable due to the data protection and sensitive information policies.

The simulation of the event followed the actual events recorded by the TSO. Because of the non-linear behaviour of hydraulic turbines and voltage-dependent loads, the exact trajectory of the recorded frequency was not completely replicated, but we did aim to capture the same RoCoF and nadir as recorded.

Then, we installed an FFR source in the 110 kV Cirkovce substation and observed the system response with various nominal powers of the BESS as a FFR provision unit. The control algorithm is the same as in the other experiments.

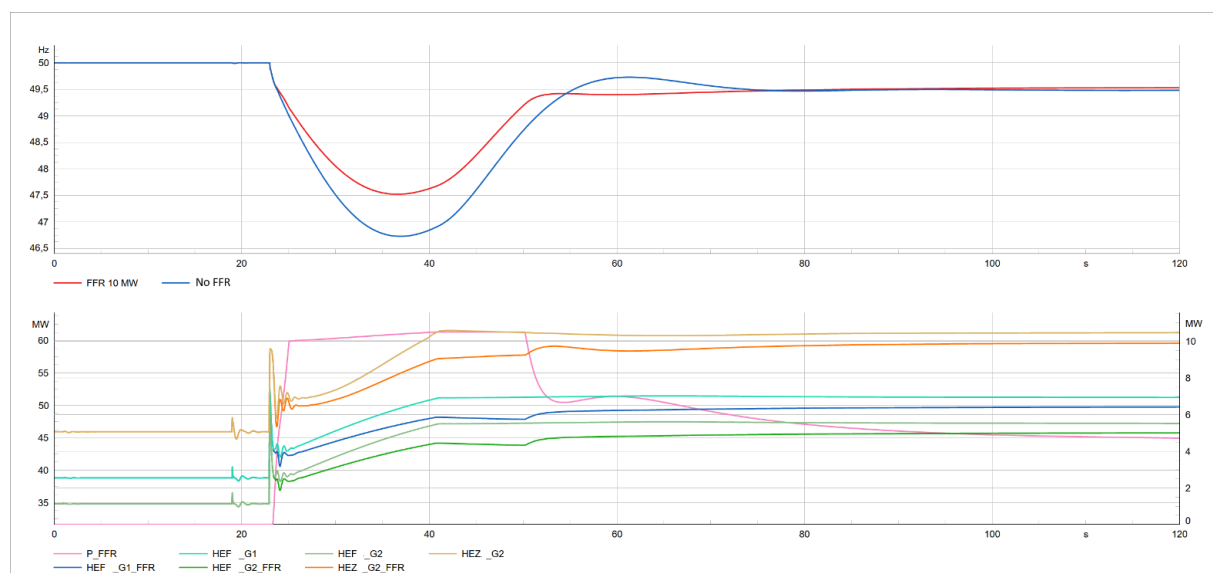


Figure 5-15: Frequency and power graphs of the islanding incident with FFR inclusion

With just 10 MW of FFR, the nadir rises from 46.7 to 47.5 Hz. The bottom graph displays the active power responses of three hydropower generators that were connected to the island, as well as the power response of the FFR source.

In this case, FFR can improve the nadir and eliminate the frequency overswing as the system stabilizes, leading to a faster steady state.

We also ran the simulation with various installed power levels to see how they influence the nadir and RoCoF. Figure 5-16 displays frequency graphs for 10 or 20 MW installations compared to the case of no FFR present in the system.

Disclaimer: Some of the data and information regarding this incident and isolated operation were purposely omitted, adapted and/or masked to preserve the required anonymity and non-disclosure rules and practice between the stakeholders. However, the use-case with severe RoCoF₀ is of very high importance, in particular to demonstrate the FFR impact during such events.

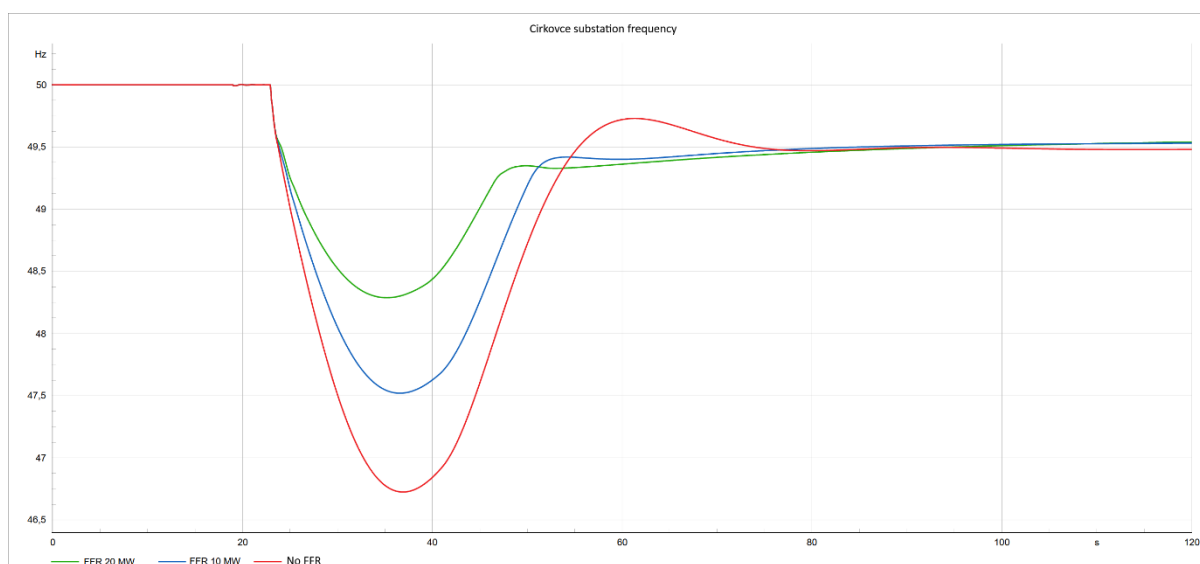


Figure 5-16: Frequency response with various installed power levels

5.4 Summary of the key findings of the simulations

Large-scale dynamic simulations demonstrate that FFR can have a significant influence on frequency behaviour in both system-wide and local operating scenarios. Its impact is particularly pronounced in smaller islanded network areas, where low effective inertia and substantial power imbalances can result in rapid frequency changes.

Although several scenarios represent deliberately severe or low-probability operating conditions, the proposed FFR algorithm did not introduce adverse oscillations or additional instability, including in smaller islanded systems that are inherently more vulnerable to dynamic disturbances.

The FFR approach considered in this task does not introduce any instability even in smaller islanded parts of the system that could otherwise be prone to stability issues.

Overall, the proposed FFR response reduces the duration and severity of the frequency transient, improves the frequency nadir, supports frequency arrest, and facilitates the return of system frequency towards the applicable operational tolerance range.

5.5 Disclaimer on the real-system testing

The original TwinEU demonstration concept considered the possibility of validating FFR through real-system testing. Following a technical, operational and stakeholder risk assessment, deliberate system-level triggering of FFR was not considered proportionate or sufficiently safe within the scope of this task. The FFR demonstration was therefore performed through a very detailed dynamic simulations using the digital twin environment instead of intentionally creating severe frequency disturbances in the actual Slovenian power system.

The proposed FFR characteristic starts activating at an absolute frequency deviation of 200 mHz and reaches full activation at 800 mHz. As previously mentioned, for the Continental Europe synchronous area, SOGL defines 200 mHz as the maximum steady-state frequency deviation and 800 mHz as the maximum instantaneous frequency deviation. Under Article 18 of the SOGL, the system enters the emergency state when frequency no longer satisfies the criteria for the normal or alert state, when an operational security limit is violated, or when a system-defence-plan measure is

activated. Strictly, a momentary crossing of the 200 mHz threshold does not, by itself, prove that the system is already in the emergency state, because the regulatory classification also depends on the duration of the deviation and other operational-security criteria. However, a deliberate full-scale test intended to reproduce the complete FFR activation range, particularly up to ± 800 mHz, would require a substantial active-power imbalance, islanding event or comparable severe disturbance. The system-level scenarios for which FFR is primarily relevant—such as system splits, isolated operation, major generation or demand losses, and restoration processes—are therefore associated with emergency, blackout or restoration conditions rather than normal system operation. The Network Code on Emergency and Restoration specifically governs the management of these states and the activation of system-defense and restoration procedures.

Deliberately creating such conditions in the real transmission system would expose the system and its users to risks that are not justified by the objectives of the demonstration. Potential consequences include an uncontrolled frequency or voltage excursion, loss of synchronism, unintended protection operation, collapse of the tested island, equipment stress, interruption of supply and propagation of the disturbance beyond the intended test area. Stakeholders input similarly identified the potential for system collapse, damage to end-users and the need for the TSO to assume responsibility and accountability for the associated operational risks. A controlled island without significant demand was considered less risky, but also less representative and dependent on an artificial balancing load.

The regulatory framework also establishes a clear safety principle for system testing. Article 43(4) of the NC ER requires that tests of relevant system capabilities must not endanger the operational security of the transmission system or interconnected system and must be conducted so as to minimize the impact on system users. A deliberately induced system-wide frequency excursion would be difficult to reconcile with this principle unless it were performed under a dedicated wider TSO-approved test plan, within a fully controlled test island and with clearly allocated operational and liability responsibilities.

The economic exposure further supports the decision not to perform deliberate real-system disturbance testing. Some of the stakeholders in Slovenia cited an indicative Value of Lost Load assessment for Slovenia of approximately 16.000 EUR/MWh. Even a relatively short interruption affecting a significant amount of demand could therefore create material socioeconomic costs, in addition to possible equipment damage, operational recovery costs and reputational consequences. This value is used here as an indicative risk parameter rather than as a definitive project-specific damage estimate.

For these reasons, the real-system demonstration envisaged at the proposal stage was replaced by simulation-based validation using the WENDY dynamic modelling environment. The simulation framework enables the analysis of the interconnected Slovenian control area, islanded operation of the national system, regional islands, hydropower-plant chains, system-split scenarios and recorded islanding incidents. It also allows controlled comparison of cases with and without FFR, systematic variation of inertia and disturbance severity, and repeatable assessment of RoCoF, frequency nadir, frequency arrest and FFR activation parameters without exposing the actual power system to operational risk.

The use of simulations should not be interpreted as eliminating the need for future physical verification. Before operational deployment, individual FFR providers will still require prequalification and compliance testing. Such verification may be performed through hardware-in-the-loop testing or carefully staged field tests.

Accordingly, the deviation from the original real-system demonstration concept is considered technically justified, proportionate and consistent with operational-security requirements. Within the scope of this deliverable, detailed dynamic simulation provides the safest and most appropriate method for demonstrating the expected system-level impact of FFR. Any future real-system testing should be subject to a separate TSO-led risk assessment, an approved test plan, clearly defined liability, accountability and responsibility, detailed arrangements and confirmation that the test cannot endanger system users or the interconnected power system.

6 Conclusions

The executive level conclusions are:

1. FFR is a crucial service for stable operation of the system, in particular for the frequency stability during large-frequency deviation states, and further in emergency states, blackouts and restoration, thus including:
 - System splits
 - Small isolated system operation in an island
 - Resynchronization of the system
2. Market and regulatory aspects remain a challenge and represent an opportunity for further work.
3. Stakeholder analysis regarding the FFR (in Slovenia):
 - expressed technical willingness and preparedness but
 - raised concerns regarding market feasibility and techno-economic viability.

The details of the conclusion are divided into two logical groups:

- Key findings
- Further work proposal

6.1 Key findings

1. TwinEU Task 7.7 delivered an integrated FFR concept. The work defined the service purpose, activation algorithm and product with technical and system requirements, planning methodology, provider conditions, regulatory basis, market concept, use cases and simulation-based demonstration. It therefore directly addresses the task objectives and links digital-twin capabilities with a deployable ancillary-service proposal.

2. FFR should be classified as a dedicated frequency-related ancillary service. It is a reserved, prequalified and verifiable very fast active-power response to frequency deviation. It is distinct from natural and synthetic inertia, mandatory LFSM and FSM capability, market-based FCR and system-defence measures, while remaining technically coordinated with all of them.

3. The proposed product has a clear and defensible activation envelope. FFR remains inactive within ± 200 mHz, activates proportionally beyond that boundary and reaches full activation at ± 800 mHz. The response should start without intentional delay, begin within 0-100 ms, reach full delivery within 200-400 ms, remain fully available for 2-30 s and deactivate in coordination with slower frequency controls. Compliance must be based on active power delivery performance at the point of common coupling.

4. The activation thresholds protect the existing frequency-control architecture. The ± 200 mHz boundary corresponds to the Continental Europe maximum steady-state frequency deviation and FCR full-activation deviation, while ± 800 mHz corresponds to the maximum instantaneous frequency deviation. Keeping FFR outside the routine FCR range limits product overlap, protects FCR market liquidity and avoids an immediate redesign of the harmonized FCR process.

5. The sensitivity analysis identified the decisive design relationships. The disturbance-to-FFR ratio determines whether the available capacity can arrest the frequency: a ratio below one provides margin, a ratio equal to one is the limiting complete-coverage case, and a ratio above one means that FFR alone cannot compensate for the disturbance. Even with sufficient capacity, the nadir remains strongly dependent on initial RoCoF, activation delay and full-activation time.

6. Inertia and FFR must be planned jointly but are not interchangeable. Inertia and disturbance size determine the true initial RoCoF and the time available before threshold activation of FFR; threshold-based FFR changes the subsequent trajectory rather than the initial RoCoF. The proposed analytical framework is suitable for first-step screening, but final capacity and performance requirements must be derived from credible disturbances and validated in detailed time-domain simulations.

7. FFR requires nodal, locational and unit-level planning. The initial implementation should focus on directly transmission-connected providers at 110 kV, 220 kV and 400 kV, supported by geo-electrical dispersion and coordination with the potential island and restoration configurations according to the national defense and restoration plans. For multifunctional units, the indicative contribution range of 0.05 pu minimum, 0.16 pu preferred and 0.32 pu recommended upper limit of FFR-to-nominal power ratio supports portfolio diversity and limits concentration risk. For units dedicated exclusively to FFR provision, no fixed per-unit limit is proposed; the accepted capacity should instead be determined by system needs, technical capability and techno-economic feasibility. Larger contributions from individual dedicated units should be accepted only after the provider and the TSO have jointly tested and validated the units' FFR settings and capabilities, and interaction with other system controls, confirming that the proposed response does not adversely affect system security and stability.

8. Provider eligibility should remain performance-based and technology-neutral. However, BESS are the most immediately suitable candidates because of their fast bidirectional control, modest energy requirement and precise verification and performance. Power park modules, highly controllable demand, transmission charging infrastructure, HVDC and other flexibility resources or storage modules may also qualify where dedicated power headroom, energy sufficiency, measurement quality, autonomous activation, repeatability and controlled recovery are demonstrated.

9. The WENDY digital-twin-oriented environment provided a credible demonstration pathway. The highly detailed European and Slovenian model enabled repeatable assessment of a European system split, national islanding, the Severna Primorska loop, the Drava hydropower chain and a reconstructed 2026 Slovenian-Croatian islanding incident. This created a practical bridge between product design, planning, safe demonstration and future deployment.

10. The simulations confirmed a substantial, adequate and stable FFR contribution. FFR improved the frequency nadir, supported frequency arrest and shortened frequency transients, with the greatest benefit in smaller islanded areas. The proposed algorithm did not introduce adverse oscillations or additional instability in the analysed scenarios.

11. Simulation-based demonstration was technically justified and proportionate. Deliberately creating the power system conditions, in particular the severe frequency deviations required for full-scale activation would expose the real system, equipment and users to unacceptable security, stability and wider socio-economic risks. Future physical demonstration should therefore proceed through hardware-in-the-loop assessment and/or be carefully executed by field tests at least under TSO-approved risk framework.

12. The initial market concept should be availability-based and limited to one control area. FFR creates value through continuously reserved and verified active-power capability rather than energy delivery. Annual or multi-year ex ante contracts are a pragmatic development-stage solution. No exchange or sharing between control areas should be permitted due to the nature of the FFR purpose and objectives. Stakeholders show technical willingness, particularly for BESS, but market feasibility and techno-economic viability remain conditional. Local bidding markets may be explored at a later stage.

13. The regulatory gap is both a challenge and an opportunity. No harmonized European FFR product is currently defined. Existing EU regulation and national law provisions provide enabling concepts but not a ready-to-use legal product. TwinEU supplies the technical evidence, product logic, use cases and implementation pathway needed for further scalable and adaptable European and national FFR development.

14. International practice confirms that no universal FFR design exists. The reviewed systems use different products because their synchronous-area size, inertia, credible disturbances, network configuration, provider mixture and market architecture differ. International experience should therefore guide, but not replace, a system-specific Continental Europe and Slovenian design.

6.2 Further work proposal

6.2.1 FFR vs. FCR threshold adaptation and further coordination

As the power-electronics technologies emerge and the system development tends towards the omission of the conventional inertia, further work should assess a coordinated redesign in which FCR reaches full activation at lower frequency deviations, for example ± 100 mHz, instead of the current ± 200 mHz, while FFR begins activating at the same ± 100 mHz boundary. Under this approach, FCR would provide the complete first layer of slower frequency containment within the narrower deviation range, and FFR would provide an additional, faster response as the frequency deviation increases beyond that range. The FFR characteristic could then continue towards full activation at the defined outer frequency-deviation threshold.

Such a change would require substantial regulatory, technical and market coordination. Reducing the FCR full-activation deviation would affect FCR dimensioning, procurement, remuneration and market liquidity. Any implementation should therefore be supported by detailed dynamic studies, coordinated stakeholder consultation and agreement at both national and Continental Europe synchronous-area level.

6.2.2 Regulatory challenges and opportunities

A staged regulatory pathway is necessary.

Further work should at first establish an explicit legal classification and national product definition for FFR. The Slovenian regulatory and operational framework should then be adapted accordingly. This includes national legislation, system operating instructions, market rules, connection procedures, contractual arrangements and technical guidelines. The final framework should especially ensure consistency between the technical product definition, operational implementation and market procurement.

Institutional responsibilities and liability must also be clearly allocated.

FFR should also be coordinated with system-defence, restoration and risk-preparedness frameworks. Unless explicitly designated otherwise, it should remain legally distinct from defence and restoration services. Nevertheless, its location, capacity and availability should be considered in planning for system splits, islanded operation, blackout conditions and resynchronization.

6.2.3 Usage of HIL

The Fast Frequency Response (FFR) functionalities defined within TwinEU require rigorous validation under realistic dynamic conditions before deployment. It is recommended to establish an RTDS-based Hardware-in-the-Loop (HIL) setup, enabling closed-loop interaction between physical controllers and a detailed power system model. This allows direct verification of key requirements such as activation delay, power ramp characteristics, accuracy of response, and impact on system frequency and stability margins. Attention must be given to the definition of benchmark system models, representative disturbance scenarios, and minimum expected performance criteria, as these form the basis for consistent and reproducible testing. The HIL environment further enables assessment of interactions with existing protection schemes and coordination across heterogeneous assets. FFR implementation risk is non-negligible, as FFR involves very fast active power injections or reductions that directly influence system dynamics; improper behaviour can lead to adverse interactions or stability degradation. A controlled HIL framework therefore provides a necessary step to identify such risks early and ensure compliance with the specified functional requirements.

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