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
CA	Control Area
CB	Control Block
CEP	Clean Energy Package
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
DER	Distribute Energy Resource
DSA	Dynamic Security Assessment
DSO	Distribution System Operator
DTW	Digital Twin
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
HV	High Voltage
LFC	Load-Frequency Control
LV	Low Voltage
MV	Medium Voltage
OLTC	On-Load Tap Changer
PGM	Power Generating Module
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 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 is the 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

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.

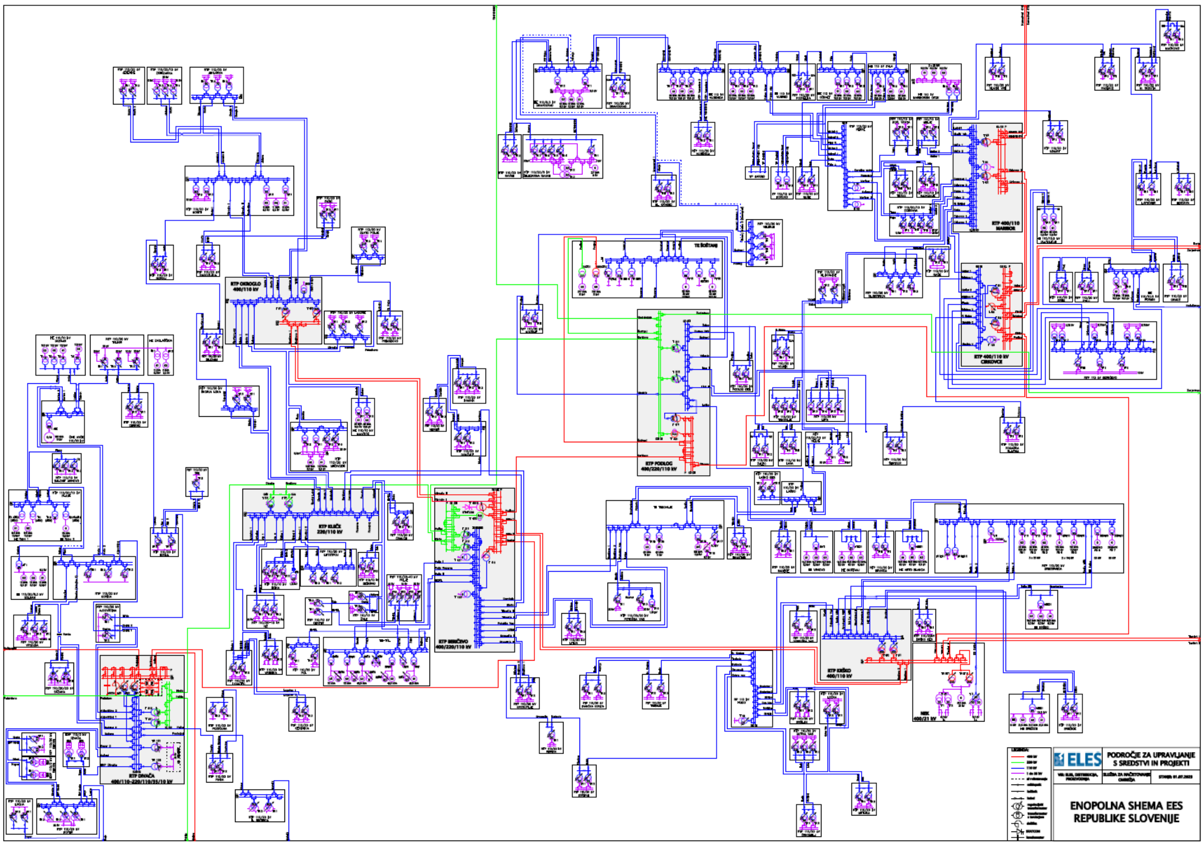

Figure 1-1 – Slovenian Electric-Power System (Single-line diagram of the 400, 220 and 110 kV level)

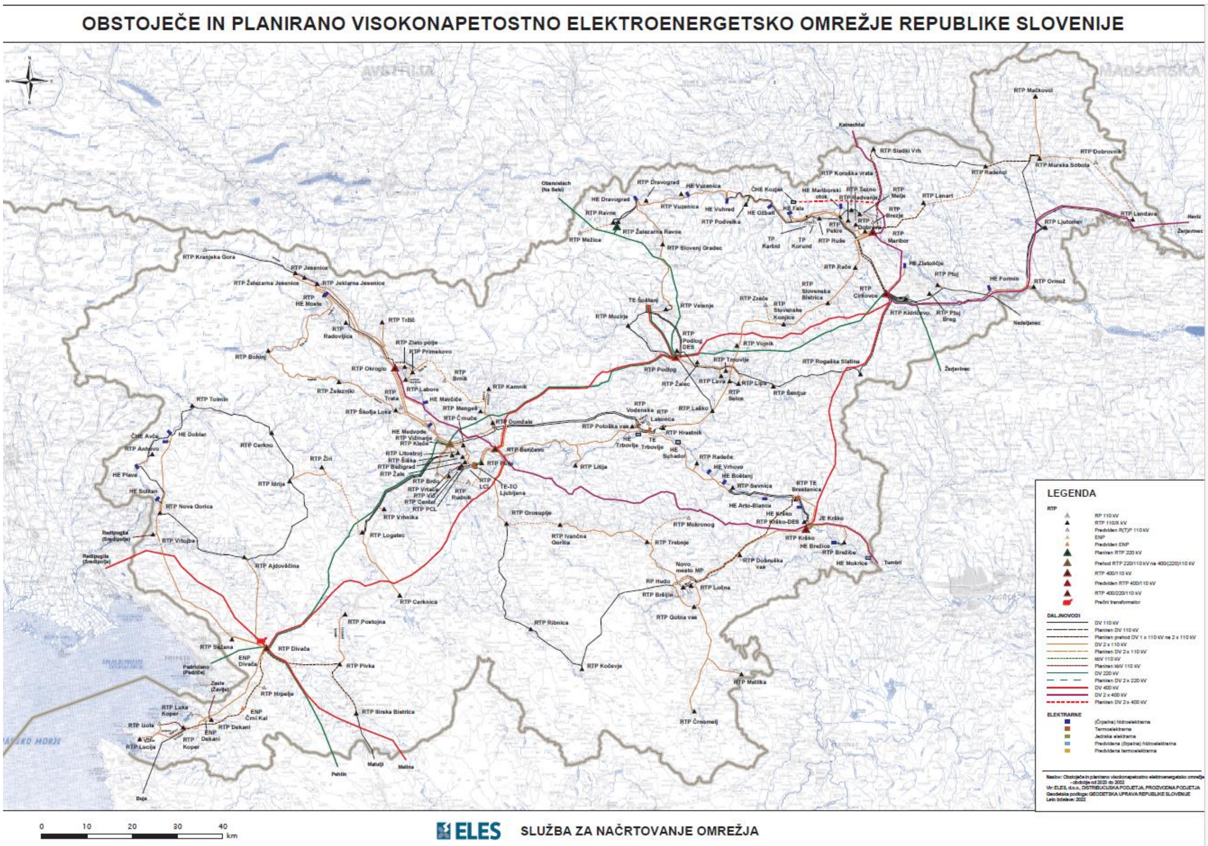

Figure 1-2 – Slovenian Electric-Power System (Geographic diagram of the 400, 220 and 110 kV level)

Key aspects 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 is 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. 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.

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) a similar simulation models created in DIgSILENT Power Factory were used but nevertheless differ based on the execution of the tests and the objectives of the activities. The model used in this Deliverable 7.5 (result of the activities within the Task 7.7) will be further described.

1.3 How to Read this Document

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.

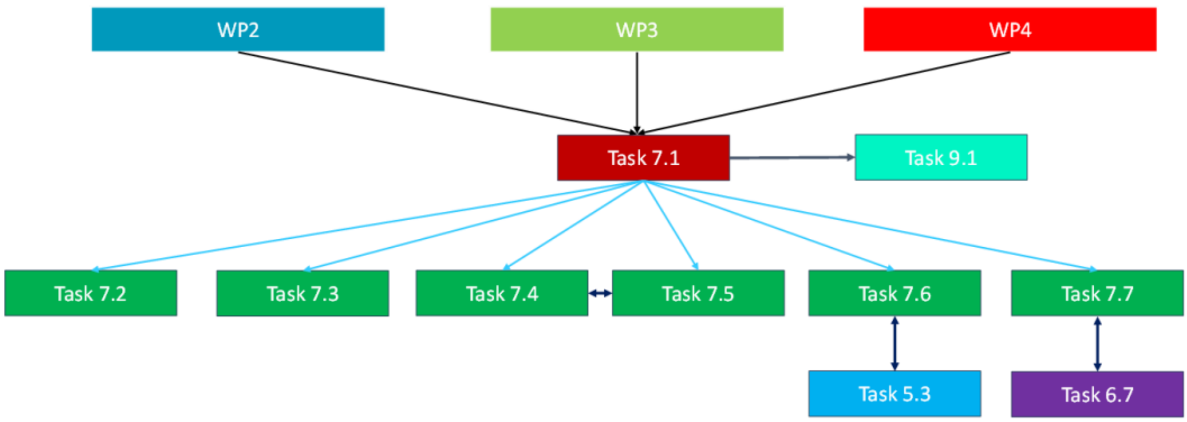

Figure 1-3 - Task relations

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 balancing service in Continental Europe. This service is provided by Fast Frequency Reserve (FFR). Objectives of the task 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.

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, market and mathematical contributions of the Slovenian partners.

2.1 The crucial aspects and questions

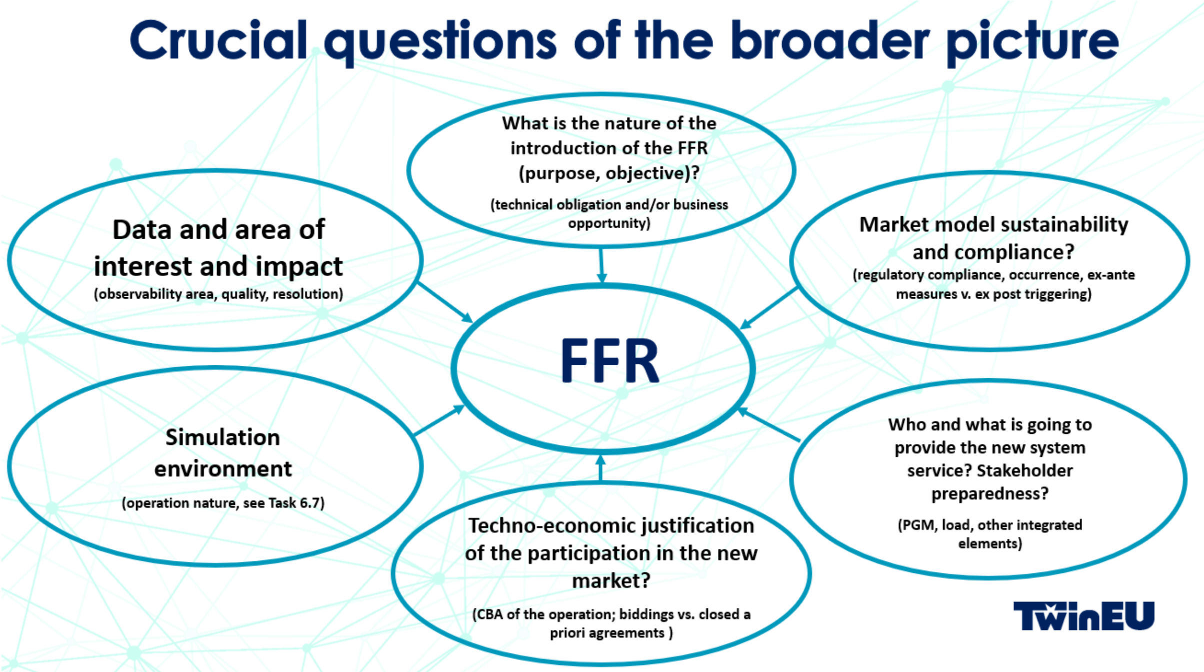

Figure 2-1 - Crucial question of broader meaning of the FFR service proposal

2.2 The nature of the FFR and its challenges

2.3 Our FFR development guidelines

For the purpose of the FFR service concept development we followed the objectives of the task as well as our a-priori internal guides that:

- FFR should be **simple** service: **scalable, non-discriminatory, symmetrical**. Different classes of FFR would be developed only if technically justified according to the technology capabilities.
- FFR provision should be **continuous**, and its activation very **carefully selected**, all for the purpose of security and stability of the electric power system.
- FFR should be **precise** in ms time resolution.
- FFR should have **short duration of activation**.

FFR provision will create a **market of wider character** (Continental Europe) but of **local influence**.

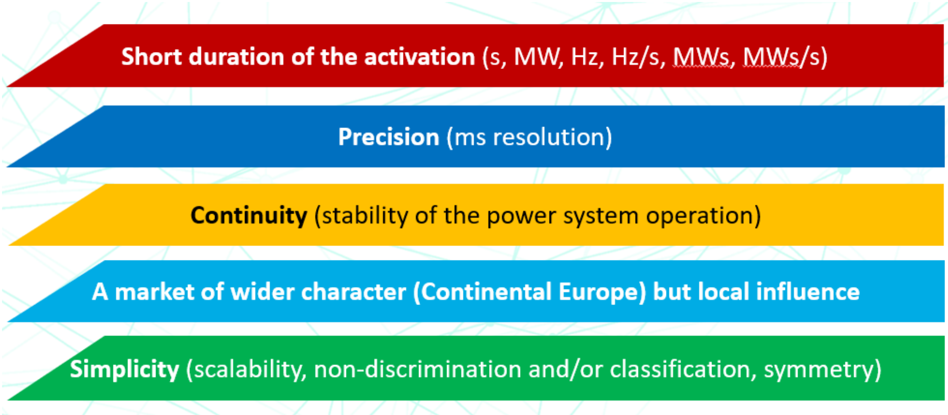

Figure 2-2 - FFR development guidelines

2.4 International best practice examples

2.4.1 Nordic practice

2.4.2 Australian practice

2.4.3 Great Britain practice

2.4.4 Irish and Northern Irish practice

3 Regulatory-technical basis

.

3.1 System operation guidelines (SOGL)

3.1.1 Electric power system states

3.1.1.1 Tolerable frequency nadir

Figure 3-1 - Frequency nadirs in different power states

3.2 Requirement for Generators (RfG 1.0, 2016, vs. novel proposal RfG 2.0, 2026)

3.3 Clean energy package (CEP) of regulations and directives (2019/941-944/EU and their renewals in 2024)

3.4 Other significant regulatory bases

4 The FFR concept

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4.1 The definition of the FFR

4.1.1 Product formulation and visualization

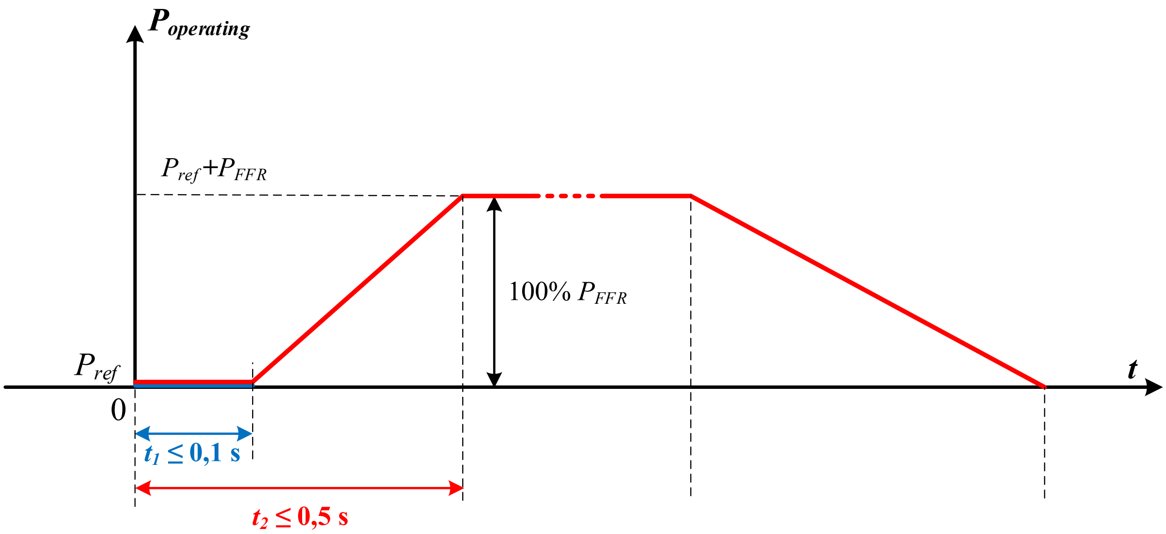

Figure 4-1 - P-t diagram of the FFR (FFR product visualization)

4.1.2 Algorithm for service activation

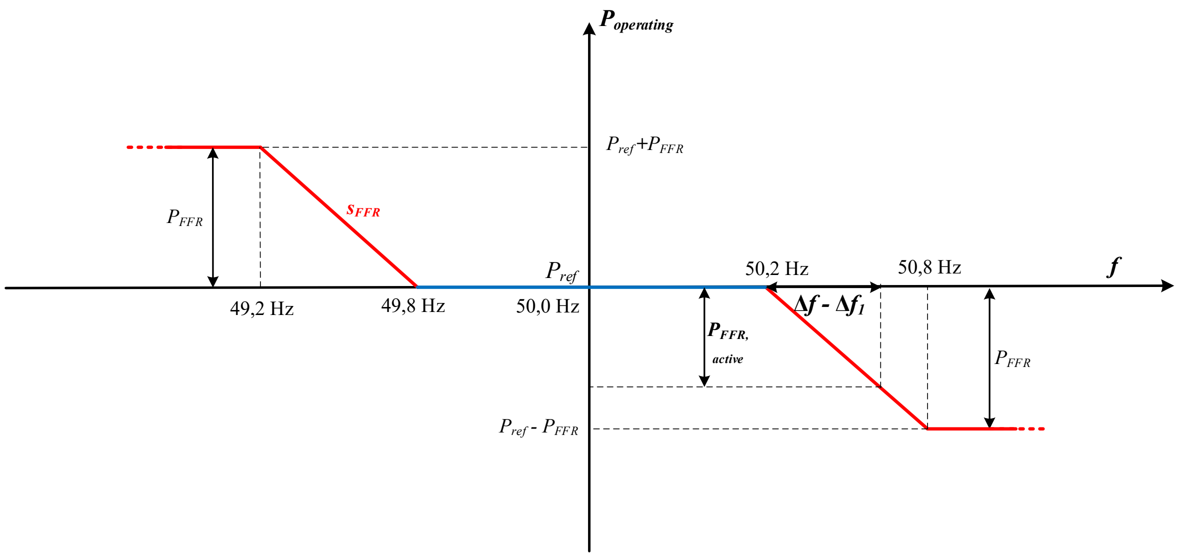

Figure 4-2 - P-f diagram of the FFR - algorithm visualisation 1

$$P_{operating} = P_{ref} - \underbrace{\frac{\Delta f - \Delta f_1}{\Delta f_2 - \Delta f_1} \cdot P_{FFR}}_{P_{FFR},active} \quad (4.1)$$

$$P_{operating} = P_{ref} - \underbrace{\frac{\Delta f - 0{,}2\ \text{Hz}}{0{,}8\ \text{Hz} - 0{,}2\ \text{Hz}} \cdot P_{FFR}}_{P_{FFR}{,}active} \quad (4.2)$$

$$s_{FFR} = \left| \frac{\frac{\Delta f_2 - \Delta f_1}{f_n}}{\frac{P_{FFR}}{P_n}} \right| \quad (4.3)$$

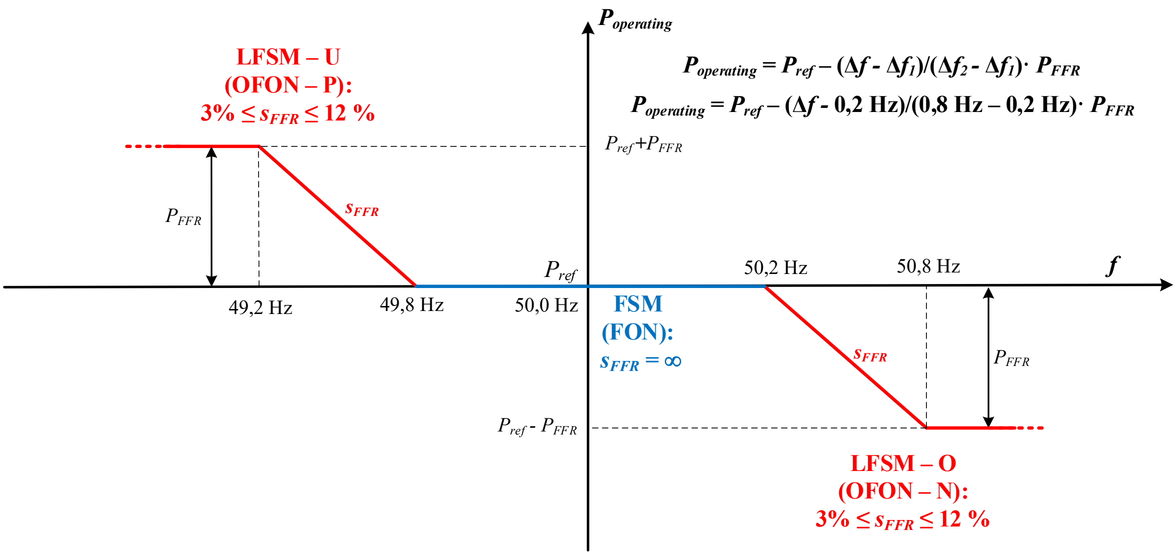

Figure 4-3 - P-f diagram of the FFR - algorithm visualisation 2

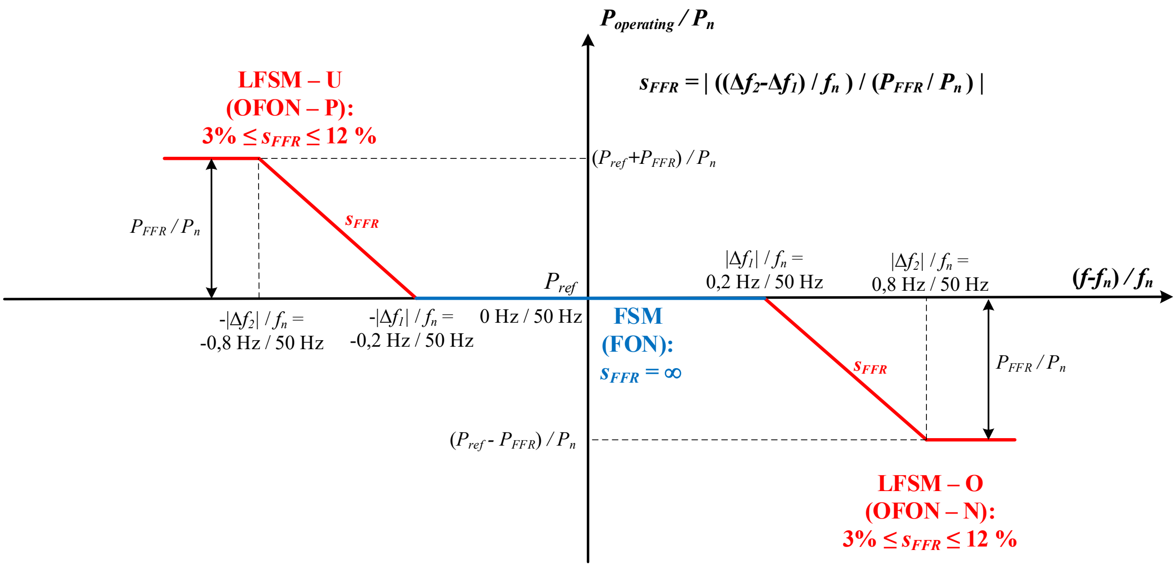

Figure 4-4 - P-f diagram of the FFR - algorithm visualisation 3

4.1.3 Distinction from the SPGM's natural inertial response, GFM's synthetic inertia response, GfM delayed inertia response and FCR response

4.2 Dimensioning of the FFR with distinguished control area and unit level

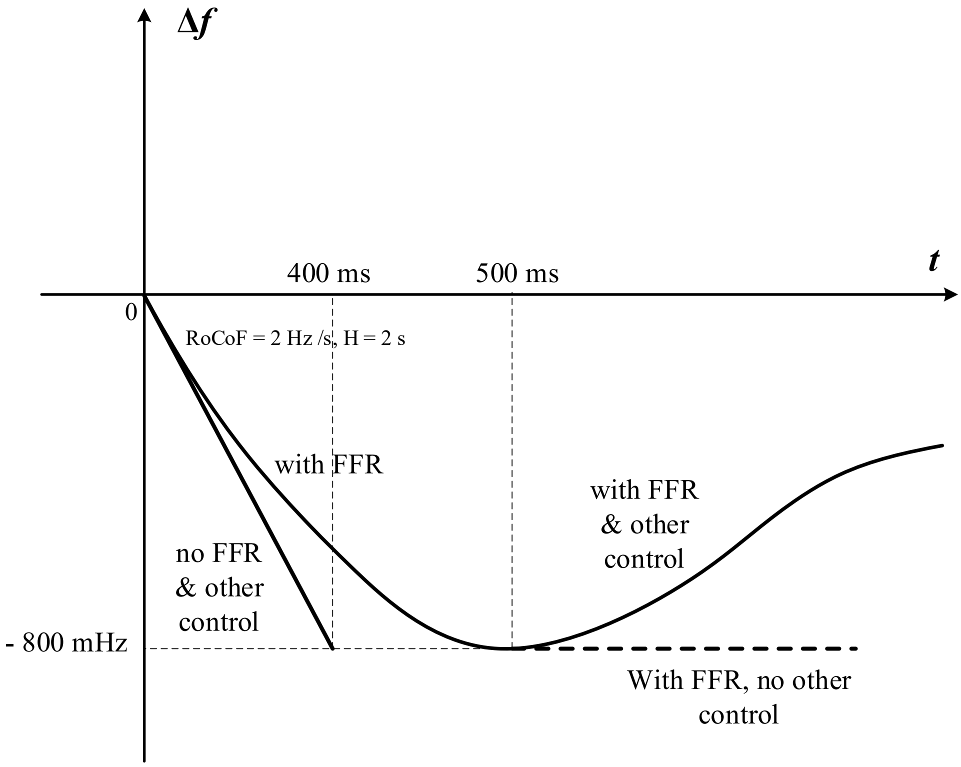

Figure 4-5 - Frequency deviation with and without FFR

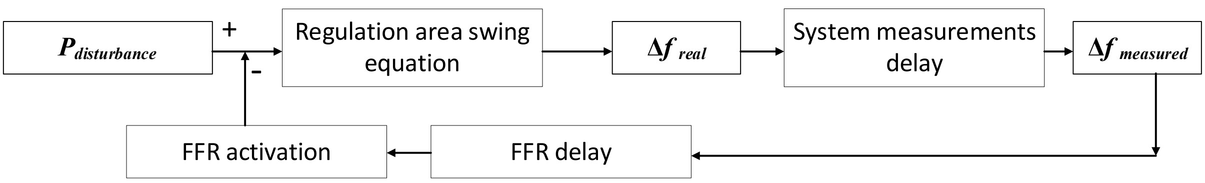

Figure 4-6 - Simplified FFR block diagram

$$\frac{2H}{f_n} \cdot \frac{df}{dt} = \frac{\Delta P_{imbalance}}{P_{net\ demand,CA}} = \frac{P_{disturbance}(t,f) - P_{FFR,total\ CA}(t+delay,f)}{P_{net\ demand,CA}} \qquad (4.4)$$

where:

- $\Delta P_{imbalance}$ is power imbalance in the control area,
- t is time measured with ms resolution,
- f frequency at the point of common coupling,

- …

$$P_{FCR_{area\ total}} \leq P_{FFR_{area\ total}} \leq percentage\ of\ P_{net\ demand\ in\ the\ CA} = percentage\ of\ P_{net\ demand\ in\ the\ CA} \qquad (4.5)$$

4.2.1 FFR dimensioning example in the Slovenian control area

$\frac{\Delta P_{imbalance}}{P_{net\ generation,CA}}$ = 16 %, yielding FFR total between 14 MW – 320 MW, assuming the Slovenian net generation is approx. 2000 MW at some crucial state of the electric power system.

4.3 Market aspects and pricing

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

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

Table 4-1 - 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)	100 ms - 200 ms (TBD)	***t*** $_1$	***t*** $_2$
Rise time to a full activation	200 ms - 500 ms (TBD)		
Full activation sustainability	up to 30 s		
Decline time after a full activation	no more than 30 s, depending on the FCR activation		
Frequency sampling resolution	20 ms		
Point of common coupling	Transmission-connected (400, 220, 110 kV)		

Table 4-2 - High-level overview of the FFR service

	Fast Frequency Response (FFR) - high-level overview
What is FFR?	FFR is a frequency control expressed as fast active power response to a frequency deviation via very sensitive droop P-f control of qualified providers
What frequency?	Filtered local frequency at the PCC
Who/What?	Qualified transmission-connected providers: - power generating modules (type D according to RfG 2.0, mainly power-park modules), - demand facilities, - electricity storage modules, - electrical charging parks *Transmission-connection is considered 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.
Regulatory basis and compliance:	CEP 2019: Regulation 2019/943/EU and Directive 2019/944/EU (as of 16.7.2024) National Electricity Supply Act
Technical criteria basis:	RfG 2.0; NC DC 2.0 (as of 2025): https://www.acer.europa.eu/sites/default/files/documents/Recommendations_annex/ACER_Recommendation_03-2023_Annex_1a_NC_RfG_TC_to_original.pdf National electric power system operation guidelines (as of 2025) Rules and conditions for FFR providers (equvivalent to the ones for FCR providers)
System criteria basis:	SOGL, NC ER, National electric power system operation guidelines (as of 2025)
Unit provision of FFR [pu]	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, preffered is 0,16 pu. Larger unit provision of FFR is not reccomended. The providers and the TSO must be test the droop setting 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 Hmin 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. Minimum requirement is equal to the FCR mandatory provision. Preffered is 0,16 pu of the net generation in the control area at a certain crucial state defined by the TSO or TSOs. Larger total control area provision of FFR is not reccomended. It si strongly reccomended that the TSO simulates the activation of FFR to analyse the stability of the system.
Market:	Not more than one regulation area. No exchange nor sharing is permitted. Closed a priori annual agreements are encouraged during the development phase of the new FFR service to prevent a threat to market liquidity. In the future a local bidding markets can be further explored.
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, ie. System level) & Group II (110 kV, ie. 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

5.1 Simulation model of the electric power system

5.2 Modelling of the FFR in the simulation environment

5.3 Simulation scenarios and key results

5.3.1 Interconnected control area of Slovenia

5.3.2 Islanded control area of Slovenia

5.3.3 The Severnoprimorska loop

5.3.4 Drava river power plant chain

5.4 Summary of the key findings of the simulations

5.5 Disclaimer on the real-system testing

6 Conclusions

6.1 Key findings

6.2 Further work proposal

References