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Article

LFC and Reserve Prequalification for Synchronization with Continental Europe Synchronous Area

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Abstract: This paper presents a comprehensive analysis of the Load Frequency Control (LFC) framework required for the synchronization of Electric Power Systems (EPSs) with Continental Europe (CE). The study focuses on ensuring stable and reliable operation of autonomously functioning EPSs by examining technical requirements and prequalification procedures for Frequency Containment Reserve (FCR) and LFC-related reserves. Numerical simulations were performed to assess system dynamic behavior under disturbance conditions. The results indicate that following a 100 MW active power loss, system frequency decreased to 49.82 Hz and was restored to the nominal 50 Hz within 9 min using FCR and automatic Frequency Restoration Reserve (aFRR). A more severe 200 MW disturbance resulted in a minimum frequency of 49.68 Hz, requiring additional activation of manual Frequency Restoration Reserve (mFRR), with recovery achieved in 18 min. In extreme scenarios involving up to 600 MW power loss, the frequency dropped below the critical threshold of 49.2 Hz, but full restoration was achieved within 36 min through coordinated activation of FCR, aFRR, mFRR, and Replacement Reserve (RR). Long-term simulations demonstrated that the Frequency Restoration Control Error (FRCE) remained within the System Operation Guidelines (SOGL) Level 1 limit for 75% of the time and within the stricter Level 2 limit for 96%, meeting CE quality requirements. The study also evaluates prequalification procedures, including technical testing, communication validation, and energy management for Limited Energy Reservoir providers, ensuring robust and non-discriminatory participation in balancing markets.

Keywords: Balancing Service Provider; Electrical Network; Frequency Restoration Control Error; Frequency Restoration Reserve; Limited Energy Reservoir; Load Frequency Control; Synchronization

1. Introduction

In recent decades, the transformation of the European electricity sector has shown that synchronization with Continental Europe (CE) is not only a technical task but also a strategic priority with major implications for energy security, reliability, and market integration. A crucial prerequisite is the ability of national Electric Power Systems (EPSs) to maintain stable frequency control and sufficient reserves in line with the requirements of the broader synchronous area. Although the literature covers many Load Frequency Control (LFC) strategies and control algorithms, most studies focus on isolated systems or purely simulation-based approaches. What remains insufficiently addressed is the practical readiness of EPSs to comply with harmonized European requirements for reserves and prequalification in the context of CE integration.

Earlier research has emphasized frequency stability under disturbance conditions, often using advanced controllers and optimization techniques. While valuable, these works tend to overlook the institutional and operational frameworks needed for real-world implementation. In particular, there is a lack of comprehensive studies linking theoretical LFC methods with the standardized prequalification procedures required by European regulation. Without this connection, theoretical models remain of limited use in actual synchronization projects [1–4].

This study addresses the gap by presenting a systematic analysis of LFC structures and reserve prequalification procedures for CE synchronization. Unlike many model-based studies, the proposed framework is supported by simulations validated against real-world EPS operational data, ensuring that results capture realistic system dynamics and strengthening the credibility of the approach.

Special focus is given to prequalification procedures, which serve as the bridge between theoretical capability and operational compliance. In practice, these include technical testing of reserve-providing units, validation of communication interfaces with Transmission System Operators (TSOs), and assessments of activation speed, ramping, and deactivation times. Standardizing such procedures ensures technical robustness, transparency, and equal conditions for all Balancing Service Providers (BSPs). Particular attention is devoted to Limited Energy Reservoir (LER) units, where energy management strategies must be demonstrated to guarantee sustainable service provision.

The contribution of this work lies in aligning national practices with CE-wide standards, as set out in the System Operation Guidelines (SOGL). While SOGL provides the regulatory foundation, practical synchronization requires detailed methodologies for reserve dimensioning, procurement, and activation. By combining simulation results with procedural analysis, this study bridges the gap between regulation and implementation, offering a concrete pathway toward stable and regulation-compliant synchronization with CE [5–7].

2. The Functional Scope and Strategic Objectives of LFC

One of the most critical processes for ensuring operational security, system reliability, and power quality is the implementation of LFC. Effective LFC is achievable only through real-time cooperation among TSOs to balance generation and demand, thereby maintaining the system frequency at 50 Hz across the Synchronous Area (SA).

This article focuses exclusively on the LFC concept in the context of synchronized operation with the CE. It does not address the isolated operation mode of the EPS block.

The provisions set forth in part IV of the SOGL, specifically on LFC and reserves, aim to establish clear, harmonized, and objective requirements for: 1. TSOs and reserve-connecting TSOs; 2. Providers operating power-generating modules; 3. Providers operating demand facilities.

These requirements are designed to enhance system security, support non-discriminatory access, and promote effective competition and efficiency in the internal electricity market. Moreover, the LFC and reserve-related provisions provide the technical framework necessary for the development of cross-border balancing markets [1].

This article investigates the structure and operational framework of LFC, including quality criteria and performance targets, reserve capacity dimensioning, reserve exchange, sharing and distribution mechanisms, and the associated monitoring requirements.

It outlines the key principles and requirements that must be followed by the EPS block, specifically: 1. LFC block structure; 2. Technical requirements and prequalification of LFC reserves; 3. Methodology for dimensioning and distributing LFC reserve capacity; 4. Principles for sharing and exchanging LFC reserves; 5. Standard products for LFC reserve capacity; 6. Standard products for LFC reserve energy; 7. LFC reserve capacity procurement process; 8. LFC reserve activation process.

3. Theoretical and Operational Principles of LFC

This article establishes the responsibility framework for LFC processes, including frequency containment and frequency restoration processes, as well as their associated quality requirements, assigning these responsibilities explicitly to TSOs. It acknowledges that, due to the inherent physical properties of synchronously operated transmission systems, frequency constitutes a shared parameter across an entire SA. Consequently, all TSOs within a SA are required to collaborate closely to maintain system frequency within acceptable operational limits. Effective cooperation among TSOs necessitates a clearly defined allocation of responsibilities for managing LFC processes, ensuring reserve availability, and establishing individualized quality objectives.

These responsibilities are harmonized across different SAs through established regulatory frameworks defining the LFC structure. This structure encompasses both the operational control processes organized under the process activation structure and geographical demarcations, governed by the process responsibility structure.

Each TSO holds specific obligations to implement and manage control processes within clearly defined geographical units: monitoring areas, LFC areas, LFC blocks, and the overall SA.

This article specifies the responsibilities of each TSO in relation to peer TSOs within the same SA, mandating their active participation in LFC processes as integral members of an LFC block, LFC area, and monitoring area, with the ultimate objective of maintaining stable system frequency and ensuring its quality [2–5].

The operation of LFC processes follows a hierarchical structure of operational areas, each bearing distinct responsibilities relative to the broader LFC framework. At the highest hierarchical level is the SA, characterized by uniform system frequency across its entirety. The CE comprises several LFC blocks, each of which contains one or more LFC areas, with each LFC area further subdivided into one or more monitoring areas. This hierarchical organization of LFC processes is depicted in **Figure 1**.

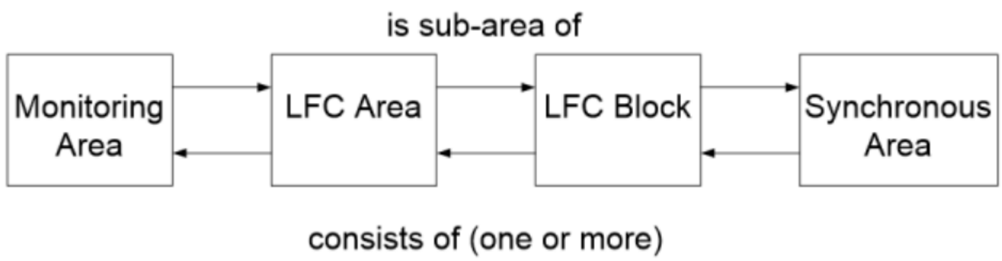

Figure 1. Structural organization of control areas in TSO operations.

Each operational area within the LFC structure has distinct obligations to ensure coordinated system operation and frequency stability across the SA.

Monitoring Area: obligated to calculate and measure active power interchange in real-time within its defined geographical boundaries. LFC Area: in addition to fulfilling the monitoring obligations, an LFC area is responsible for contributing to the achievement of frequency restoration quality target parameters by participating in the Frequency Restoration Process (FRP). LFC Block: carries the obligation to fulfil the Frequency Restoration Control Error (FRCE) target parameters by implementing the FRP. Furthermore, it is responsible for the dimensioning of both Frequency Restoration Reserve (FRR) and Replacement Reserve (RR). Synchronous Area: the overarching structure within which the system frequency is uniform. The SA is responsible for achieving frequency quality target parameters through the implementation of the Frequency Containment Process (FCP).

3.1. Organizational and Functional Framework for LFC Implementation

The SA represents the top-level structure where system frequency remains consistent across the entire area. The hierarchical framework of the LFC system is defined as follows:

1. LFC Block defines the network area for which balancing capacities are procured. It is geographically demarcated by measurement points at interconnectors connecting it to other LFC blocks and consists of one or more TSOs responsible for fulfilling LFC obligations. The LFC block is the main geographical unit for dimensioning reserves such as FRR and RR (excluding the fastest type Frequency Containment Reserve (FCR)). The LFC block is also responsible for fulfilling FRCE target parameters via the FRP.
2. LFC Area is physically demarcated by measurement points at interconnectors with other LFC areas. Operated by one or more TSOs, each LFC area is responsible for participating in the FRP to contribute to the fulfillment of the FRCE target parameters.
3. Monitoring Area is a subset of or equivalent to the entire SA, defined by interconnection points with other monitoring areas. Operated by one or more TSOs, the monitoring area is obligated to perform real-time measurement and calculation of active power interchange.
4. Scheduling Area established based on operational or organisational needs. TSOs manage scheduling obligations within this area, while Balancing Service Providers (BSPs) and Balancing Responsible Party (BRPs) are

required to adhere to the defined balancing terms and conditions.

The CE comprises multiple LFC blocks. Each LFC block consists of one or more LFC areas, and each LFC area is composed of one or more monitoring areas.

Each TSO within the CE is responsible for operating the FCP. The primary function of the FCP is to stabilize the system frequency following a disturbance, ensuring that it returns to a steady-state value within the allowable limits of maximum steady-state frequency deviation. This stabilization is achieved through the coordinated activation of FCR within the SA. The activation of FCR occurs immediately upon the detection of a frequency deviation caused by an imbalance between electricity generation and demand. The methodologies for determining the required volume of FCR are established and maintained at the SA level [3–7].

All TSOs within a LFC block that experiences imbalance are responsible for implementing the FRP. The FRP aims to return the frequency to its nominal set-point by activating FRR, thereby replacing the initially deployed FCR. The initiation of FRP is triggered within the disturbed LFC area, either automatically or manually, through the activation of FRR. The determination and allocation of required FRR capacity are managed at the LFC block level.

The Replacement Reserve Process (RRP) subsequently substitutes the activated FRR and provides additional support through the activation of RR. The initiation of RRP is likewise triggered by the LFC area experiencing the disturbance. The dimensioning criteria for RR are also defined at the LFC block level.

The sequence of activation for the various LFC reserves, along with their respective activation periods, is illustrated in **Figure 2**.

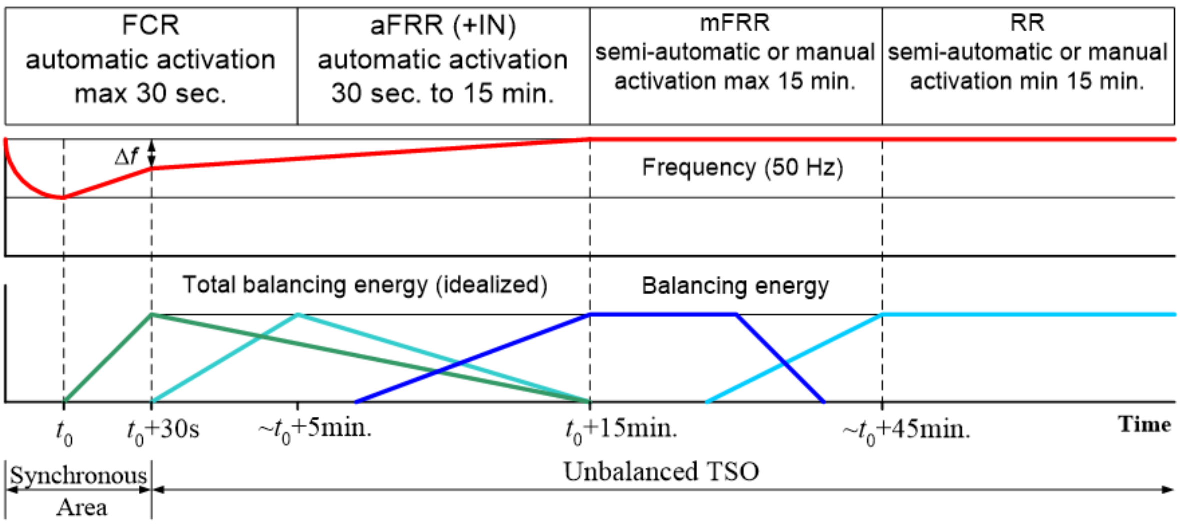

Figure 2. Balancing market structures and processes supporting frequency restoration.

4. Operational and Market Structures Supporting Power System Balancing

Balancing refers to the set of continuous actions and processes through which TSOs ensure the maintenance of system frequency within a predefined stability range, while also guaranteeing the availability and quality of the necessary reserves. These processes are fundamental to maintaining system reliability and operational security across the interconnected European power grid.

The balancing framework in Europe is governed by harmonized rules designed to facilitate the integration of balancing energy markets. These rules aim to promote effective competition, transparency, non-discrimination, and market integration. By doing so, they contribute to improving the overall efficiency of the European balancing system and strengthening the security of electricity supply. The balancing process comprises three key steps:

1. Reserve Dimensioning: TSOs assess and define the required volumes of balancing reserves based on system needs and reliability criteria;
2. Balancing Capacity Procurement: TSOs procure sufficient balancing capacity to ensure that reserves are available when needed;

3. Balancing Energy Procurement: TSOs activate and procure balancing energy in real-time to address system imbalances.

Furthermore, the balancing rules are designed to ensure a level playing field and fair competition among all market participants, including demand-side response aggregators and distributed energy resources connected at the distribution level. This inclusive approach enables more efficient use of available flexibility and supports the development of innovative balancing services [8–10].

Definition and Methodology of FRCE Performance Target Values

One of the core obligations of the TSOs within a LFC block is to strive to meet the FRCE target values. These target values, defined at the LFC block level, are an integral component of the SA operational requirements.

The FRCE target parameters serve as measurable indicators to facilitate the continuous assessment of the control performance of each LFC block and, where applicable, its constituent LFC areas. The control performance is evaluated using two predefined performance levels: 1. Level 1: the FRCE must remain within the specified limit for at least 70% of the time intervals over a given year (i.e., it may exceed the limit for no more than 30% of the time); 2. Level 2: the FRCE must not exceed the corresponding stricter limit for more than 5% of the time intervals annually.

These levels provide concrete thresholds for assessing compliance with frequency control quality and stability standards.

In accordance with CE requirements, TSOs are obligated to define the FRCE target parameters for their respective LFC blocks within the Synchronous Area Operational Agreement (SAOA). If a particular LFC block comprises multiple LFC areas, the FRCE target values for each area must also be specified in the LFC Block Operational Agreement (LFC BOA), through a coordinated process involving all TSOs of the block [11–13].

The methodology for determining the FRCE target values involves a structured, stepwise approach that includes the following elements: 1. Identification of relevant system characteristics and historical performance data; 2. Quantification of acceptable frequency deviations based on system reliability criteria; 3. Statistical evaluation of Area Control Error (ACE) profiles; 4. Definition of Level 1 and Level 2 threshold values in accordance with SA requirements; 5. Periodic monitoring and validation against real-time operational data.

This methodological framework ensures that FRCE targets are not only consistent with the operational reliability of the synchronous area but also transparent and reproducible for regulatory oversight and internal performance review. The calculation methodology encompasses these steps:

1. The frequency behaviour can be considered as a sum of two uncorrelated components, the quarter-hourly frequency average f_{qh} and the deviation from this average, the frequency noise Δf_{ns};
2. Both signals, f_{qh} and Δf_{ns}, can be approximately modelled as normal distributions with mean value equal to zero;
3. The sum of ACE values of the SA is equal to the frequency deviation multiplied with the total *k* factor of the SA;
4. The ACE behaviour of the LFC blocks is not correlated;
5. The ACE of a LFC block can be approximately modelled as a normal distribution with mean value equal to zero.

The main steps for the calculation of level 1 and level 2 ACE targets for the individual LFC blocks are the following:

1. Calculate the distribution of frequency noise;
2. Calculate the distribution of quarter-hourly frequency average values which after convolution with the frequency noise distribution will fulfil the frequency quality target parameter;
3. Calculate the frequency deviations for the probabilities defined by level 1 and level 2;
4. Calculate the shares of each LFC block proportional to the square root of the respective *k* factor.

The determination of ACE target parameters is based on frequency data for at least one year with a measurement period equal to or shorter than 1 s.

In the first step, the average frequency f_{qh} for each quarter of an hour is calculated from the Instantaneous Frequency Data (IFD). In order to obtain the frequency deviation noise Δf_{ns}, f_{qh} is subtracted from the frequency f_{IFD}, which is based on the IFD.

$$\Delta f_{\mathrm{ns}} = f_{\mathrm{IFD}} - f_{\mathrm{qh}}. \tag{1}$$

SOGL Article 127(3) and Article 127(4) require that the range of ±50 mHz must not be exceeded for more than 150,00 min per year. Therefore, in the second step, the range of $\pm g_{\mathrm{ns}}$, which must not be exceeded for more than 15,000 min a year, is estimated based on the assumption of a normal distribution [14,15].

The probability p_{m} of exceeding the 15,000 min per year is calculated using the following equation:

$$p_{\mathrm{m}} = 1 - (t_{\mathrm{out}}/t_{\mathrm{T}}), \tag{2}$$

where t_{out}—time intervals per year outside the range of ±50 mHz, t_{T}—total time intervals per year.

In order to calculate g_{ns}, the standard deviation of Δf_{ns} (δ_{ns}) is estimated from the data and multiplied by the inverse cumulative probability value of p_{m}.

$$g_{\mathrm{ns}} = \delta_{\mathrm{ns}} \cdot p_{\mathrm{mi}}, \tag{3}$$

where p_{mi}—the inverse cumulative probability value of p_{m}, δ_{ns}—the standard deviation of Δf_{ns}.

In the third step, the value g_{qh}, which represents the same range for an allowed normal distribution of the quarter-hourly average frequency deviation, is calculated based on the assumption that the two signals are not correlated:

$$g_{\mathrm{qh}} = \sqrt{(0.05)^2 - g_{\mathrm{ns}}^2}, \tag{4}$$

In the fourth step, the ranges which correspond to the probabilities $p_{\mathrm{qh\ level\ 1}}$ and $p_{\mathrm{qh\ level\ 2}}$ required by SOGL Article 128(3) are calculated taking g_{qh} as a basis. The probabilities of level 1 and level 2 are: $p_{\mathrm{qh\ level\ 1}} = 0.85$ and $p_{\mathrm{qh\ level\ 2}} = 0.975$ [16].

For the calculation of the ranges $g_{\mathrm{level\ 1}}$ and $g_{\mathrm{level\ 2}}$, the inverse cumulative probabilities of $p_{\mathrm{qh\ level\ 1}}$ and $p_{\mathrm{qh\ level\ 2}}$ will be used.

$$g_{\mathrm{level\ 1}} = g_{\mathrm{qh}} \cdot (p_{\mathrm{qhi\ level\ 1}}/p_{\mathrm{mi}}), \tag{5}$$

$$g_{\mathrm{level\ 2}} = g_{\mathrm{qh}} \cdot (p_{\mathrm{qhi\ level\ 2}}/p_{\mathrm{mi}}), \tag{6}$$

where $p_{\mathrm{qhi\ level\ 1}}$—the inverse cumulative probability value of $p_{\mathrm{qh\ level\ 1}}$, $p_{\mathrm{qhi\ level\ 2}}$—the inverse cumulative probability value of $p_{\mathrm{qh\ level\ 2}}$.

In the last step, the level 1 and level 2 ranges (R_1 and R_2) are calculated for each LFC block. With k_{SA} as k factor of the SA expressed in MW/Hz, k_{FCR} as the total FCR of the SA and $k_{\mathrm{FCR}i}$ as initial FCR obligation of LFC block i, the targets are given by:

$$R_1 = k_{\mathrm{SA}} \cdot g_{\mathrm{level\ 1}} \cdot \sqrt{k_{\mathrm{FCRi}}/k_{\mathrm{FCR}}}, \tag{7}$$

$$R_2 = k_{\mathrm{SA}} \cdot g_{\mathrm{level\ 2}} \cdot \sqrt{k_{\mathrm{FCRi}}/k_{\mathrm{FCR}}}, \tag{8}$$

5. Operational and Technical Requirements for the Provision of FCR

FCR serves to stabilize the system frequency within the SA in response to any fluctuations in the active power balance of the interconnected EPS. Given that frequency deviations can propagate throughout the entire SA, the coordinated European system of TSOs has allocated the total FCR requirement among all TSOs within the SA and has established a framework for the FCP. Consequently, each TSO operating a LFC area under CE jurisdiction is obligated to maintain an operational FCP and ensure the availability of the dimensioned FCR capacity for its respective LFC area [17].

FCR may be delivered by any Reserve Providing Unit (RPU) that meets the stipulated technical criteria and has successfully completed the prequalification process. In general, FCR must be fully activated within 30 s by the RPU following a frequency deviation event in the EPS.

6. Performance Criteria and Prequalification Standards for FRR Resources

The primary objective of FRR and the associated frequency restoration process is to regulate the FRCE towards zero within the defined frequency restoration period in the LFC block, thereby enabling the replacement of the previously activated FCR. Adequate availability of FRR is essential to ensure the quality of FRCE control and to maintain the system within the defined operational security limits.

FRR is provided by BSPs, who are responsible for activating FRR upon instruction from their respective TSO. Two types of FRR products are recognized by TSOs: 1. Manual Frequency Restoration Reserve (mFRR) activation is performed by human operators through dispatch instructions or activation messages. The main objectives of mFRR activations are to restore the aFRR capacity, proactively mitigate expected FRCE deviations, and support system operation within secure boundaries. 2. Automatic Frequency Restoration Reserve (aFRR) activation is triggered automatically via SCADA (Supervisory Control and Data Acquisition) signals generated by the frequency restoration controller. These signals are transmitted to the BSP control system, which then manages the corresponding RPUs. The purpose of aFRR activations is to progressively release FCR capacity and restore FRCE to zero [18–21].

6.1. Operational Readiness Assessment for Frequency Restoration Reserve Participation

BSPs intending to participate in the FRR markets must prequalify their RPUs in accordance with a standardized prequalification process. All TSOs within a given LFC block are required to collaboratively develop and adhere to a common prequalification procedure. This harmonized approach ensures that both mFRR and aFRR units are valid for participation across the entire LFC block.

An RPU operated by a BSP may comprise either a single FRR-providing unit or a combination of multiple units. The prequalification process includes a series of technical capability tests, which typically assess: 1. Information exchange mechanisms between the TSO and the BSP; 2. The full activation time of the reserve unit for the relevant FRR product; 3. The ramping period; 4. The deactivation period; 5. The ramp rate applicable to the specific product. During mFRR prequalification testing, the technical minimum of the unit is determined. This value subsequently defines the maximum indivisible portion of any bid submitted by the BSP. In both aFRR and mFRR testing, the maximum bid size is also established.

All FRR capacity procured by a TSO must be made fully available (100%) by the respective BSP throughout the contracted period. Following procurement, the BSP is obligated to submit energy bids aligned with the procured capacity and in accordance with agreed-upon time intervals.

The objective of FRR capacity dimensioning is to ensure sufficient reserve availability to comply with the FRCE target parameters defined for the LFC block. Furthermore, the dimensioning aims to guarantee that the available FRR capacity is adequate to address both positive and negative LFC block imbalances for at least 99% of operational time.

These imbalances arise primarily from discrepancies between actual and scheduled generation/consumption, as well as from unplanned outages of generation units, large industrial consumers, or HVDC (High Voltage Direct Current) interconnections used for import/export.

6.2. Activation Principles and Performance Parameters of aFRR Services

aFRR is an operational reserve employed by the TSO to maintain the balance between power generation and load consumption within its control area. Additionally, aFRR is used to restore scheduled cross-border power exchanges with neighboring systems and to release previously activated FCR capacity.

The provision of aFRR by aFRR providers encompasses the following key phases: 1. Scheduling phase the provider must define a load program for the reserve-providing unit that includes sufficient upward and downward operating margins to ensure the delivery of the assigned aFRR capacity; 2. Real-time operation the provider is required to activate and deliver the assigned aFRR capacity, either partially or fully, in accordance with the real-time control signal issued by the TSO.

To be eligible as an aFRR providing unit, the unit must demonstrate the ability to control its active power output to a specific set-point value with a steady-state error no greater than ±10% of the requested aFRR volume or 0.1 MW, whichever is greater.

Furthermore, the signal resolution used by the aFRR providing unit to determine the activated aFRR quantity must be at least 0.1 MW.

Each prequalified reserve unit certified for aFRR provision must be capable of delivering the assigned aFRR continuously for at least one validity period. If a potential aFRR provider is subject to technical constraints that limit the duration of continuous aFRR delivery, the provider must specify the maximum number of continuous validity periods for both upward and downward bid volumes in the aFRR prequalification documentation.

The aFRR provider must also ensure availability during all time intervals in which aFRR energy services are offered in the balancing market. However, this availability requirement is not verified during the prequalification process; instead, it applies exclusively to the reserved capacity volumes committed during the bidding process.

An aFRR provider is classified as an aFRR provider with a LER if a continuous full activation of its aFRR capacity for a duration of two hours in either the positive or negative direction without considering the effect of an active Energy Reservoir Management (ERM) could result in the inability to sustain full aFRR delivery due to the depletion of its energy reservoir.

Each aFRR provider identified as LER must submit a detailed description of its ERM strategy, which shall include the following technical and operational information: 1. Total capacity of the energy reservoir (in MWh); 2. Operational constraints influencing the reservoir's utilization (e.g., temperature, degradation, regulatory restrictions); 3. Available/operable capacity of the reservoir under normal operating conditions; 4. Permissible charge and discharge power (in MW); 5. Planned ERM strategy, including the energy source(s) used for reservoir replenishment and discharge management; 6. Frequency and method of ERM application (e.g., continuous, periodic every 5 min, etc.); 7. Expected bidding behavior, including the typical bid size and regularity under market operation [22–25].

This information is essential for the TSO to assess the reliability and sustainability of aFRR provision from LER-type units and to ensure compliance with balancing market requirements and system stability criteria.

The aFRR service verification test is conducted by issuing aFRR activation signals to the aFRR provider. The maximum upward and downward aFRR capacities tested and subsequently prequalified are determined based on the values specified in the aFRR prequalification application submitted by the BSP.

The prequalification test follows standardized testing principles, as illustrated in **Figure 3**: 1. The bold black line represents the aFRR activation signal sent by the TSO; 2. The black dashed area illustrates the tolerance band within which the actual aFRR activation is considered acceptable [26,27].

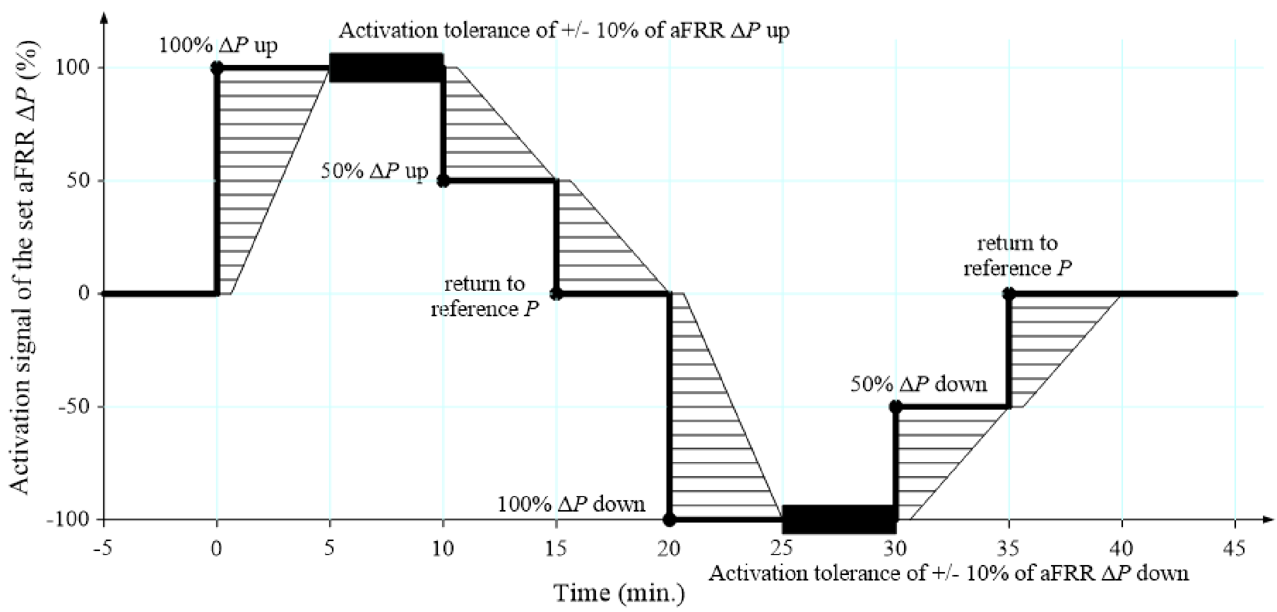

Figure 3. Standardized aFRR prequalification test plan and evaluation criteria.

This test is designed to assess whether the reserve-providing unit is capable of reliably tracking the control signal within defined technical limits and response times. Successful completion of the test is a prerequisite for participation in the aFRR market.

The recorded data from the aFRR service verification test shall be analyzed to determine the active power control parameters related to the provision of aFRR by the unit. These parameters must be evaluated and compared against the defined service requirements. The following aspects of control performance shall be assessed: 1. Activation time and full activation time. The aFRR service delivery during the activation process must remain within the black dashed tolerance band, as illustrated in **Figure 3**. This ensures that the unit follows the control signal accurately and within acceptable bounds; 2. Temporary over-fulfilment (overshoot) and control stability. The analysis shall determine whether the control exhibits overshoot beyond the requested setpoint and whether it stabilizes without oscillations or drift.

Upon activation of the aFRR service, the delivered aFRR capacity must not deviate by more than ±10% from the requested maximum service value. The response signal must remain within the black-colored band defined by the upper and lower tolerance limits, as shown in **Figure 3**.

6.3. Activation Principles and Performance Parameters of mFRR Services

mFRR represents an operational reserve utilized by the TSO primarily to: 1. Replenish the reserve capacity used during previous aFRR activations; 2. Compensate for large and sustained imbalances between actual load and generation versus their respective forecasts.

The provision of mFRR by a designated mFRR providing unit or a group of aggregated units consists of the following phases: 1. Scheduling phase the BSP must define a load program for the unit that includes sufficient upward and downward capacity margins to enable the delivery of the assigned mFRR volume; 2. Real-time phase upon instruction from the TSO, the BSP must activate and deliver the assigned mFRR volume either partially or fully in accordance with the received dispatch order.

Authorized mFRR candidates must be clearly defined and categorized based on the following attributes: 1. Configuration single units or aggregated groups of units (virtual aggregation must be supported by verifiable measurement data); 2. Type of grid user generating units, demand facilities, or storage facilities; 3. Nominal voltage level at the connection point: 330 kV, 110 kV, below 110 kV.

The mFRR activation preparation period must not exceed 7 min, meaning the activation process must begin no later than 7 min after receiving the activation signal from the TSO. The deactivation period for mFRR must not exceed 10 min.

A potential mFRR providing unit or group must be capable of adjusting its active power output to the new set-point value within the specified full activation time for mFRR. Maintaining the set-point value for the full duration of the activation as required. Delivering mFRR continuously for at least one validity period. If a technical limitation restricts continuous provision over a single validity period, the BSP must clearly specify the maximum number of consecutive validity periods and associated bid size limitations (both upward and downward) in the mFRR prequalification application. The mFRR-providing unit must be capable of controlling active power output with a steady-state error not exceeding ±10% of the requested mFRR volume or 0.1 MW, whichever is greater.

An mFRR provider is classified as a mFRR provider with a LER if a full continuous activation of its mFRR capacity lasting two hours in either the positive or negative direction could, without considering the effect of an active ERM strategy, result in an inability to sustain full activation due to energy reservoir depletion.

Each LER-type mFRR provider must submit a comprehensive technical description of its active ERM strategy. The submission must include the following details: 1. Total capacity of the energy reservoir (in MWh); 2. Operational constraints affecting reservoir usage (e.g., environmental limits, degradation factors, grid-related constraints); 3. Operable capacity under normal operating conditions; 4. Permissible charging and discharging power levels (in MW); 5. Description of the ERM strategy, including the energy source used for replenishment or discharge management; 6. Rate and frequency of ERM operation (e.g., continuous, periodic every 5 min, etc.); 7. Expected bidding behavior, including the regularity and typical size of capacity bids offered to the balancing market [22–25].

This information enables the TSO to assess the sustainability and reliability of the mFRR service provision from LER-type units and ensures compliance with operational security and market participation requirements.

The mFRR service verification test is conducted by sending predefined mFRR activation volumes to the mFRR provider. The maximum upward and downward mFRR capacities subject to testing and prequalification are based on the values submitted in the mFRR prequalification application by the BSP [26,27].

The verification process follows standardized testing principles, as illustrated in **Figure 4**, where: 1. The bold black line represents the activation order issued by the TSO; 2. The black dashed area defines the tolerance band within which the actual mFRR response must fall for the activation to be considered compliant [28].

This procedure ensures that the mFRR-providing unit or group can deliver the requested capacity accurately and reliably under real-time operational conditions.

The recorded data from the mFRR service verification test must be analyzed to derive key parameters of the active power control associated with mFRR provision. These parameters shall be compared against the balancing energy product characteristics as defined in the balancing market rules. The following control performance criteria shall be assessed: 1. Preparation period the time from the receipt of the activation signal to the start of active power response shall not exceed 7 min (i.e., 0–7 min); 2. Full activation time the sum of the preparation period and ramping period shall not exceed 12.5 min; 3. Minimum energy delivery requirement (T + 7 to T + 22 min) in both upward and downward directions, the mFRR providing unit must deliver at least 80% of the maximum activated mFRR capacity during the time interval from T + 7 to T + 22 min. The maximum activated mFRR capacity for a 15-min period is calculated by multiplying the 100% P_{up} or P_{down} value with 0.25 h to get the energy volume; 4. Maximum energy delivery limit (T + 0 to T + 27.5 min) the energy delivered during the full activation time window must not exceed 120% of the maximum activated mFRR capacity for the 15-min period, calculated using the same formula as above; 5. Signal tracking accuracy once the mFRR service is activated, the response signal shall remain within ±10% of the maximum service value. The acceptable range is bounded by upper and lower tolerance limits, as illustrated in **Figure 4**; 6. Deactivation period the mFRR providing unit must fully deactivate within 10 min following the deactivation order; 7. Temporary over-fulfilment (overshoot) and control stability any overshoot in power delivery must remain within acceptable limits, and the response must demonstrate stability without oscillation or sustained deviation. These dynamic behaviors shall remain within the black-colored tolerance band, as depicted in **Figure 4**.

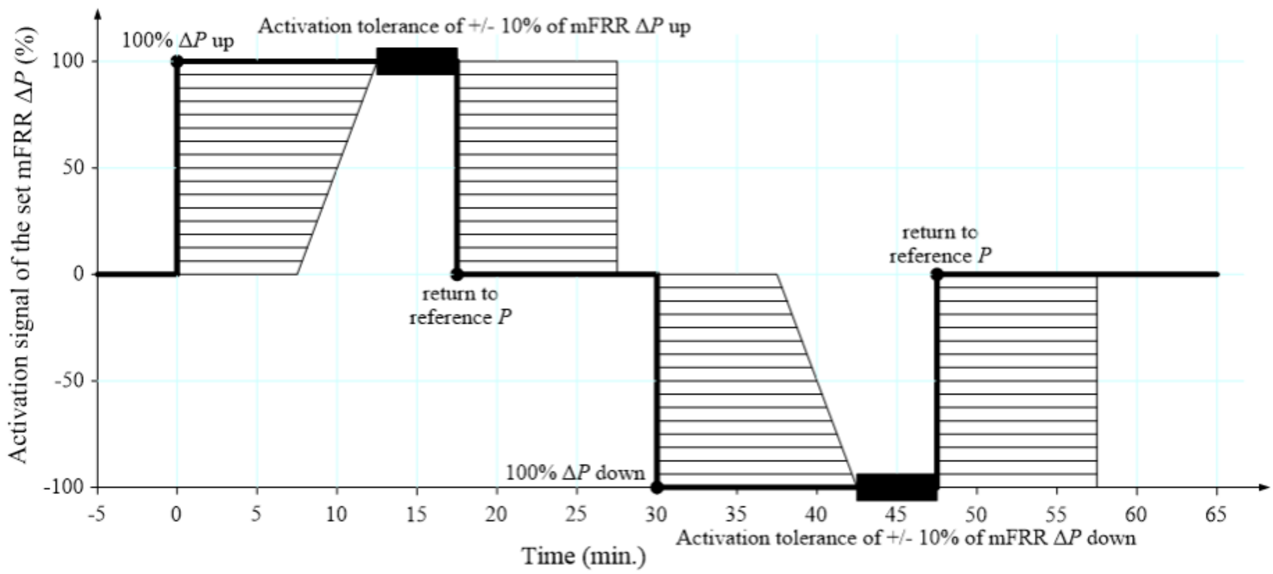

Figure 4. Standardized mFRR prequalification test plan and evaluation criteria.

7. Results

The performance of the proposed LFC and reserve prequalification framework was evaluated through numerical simulations under a range of disturbance scenarios. Two main aspects were assessed: (A) the frequency response of the EPS to different active power loads, and (B) the system's FRCE over time.

7.1. Frequency Response Analysis

Figure 5 illustrates the EPS frequency response under six disturbance scenarios: a sudden 100 MW, 200 MW, 300 MW, 400 MW, 500 MW and 600 MW active power loss. In the case of a 100 MW loss, the frequency dropped to 49.82 Hz but was quickly stabilized by FCR within 25 s. aFRR subsequently restored the frequency to nominal value within 9 min. In the presence of 500 MW loss, the frequency deviation reached 49.30 Hz. Here, FCR and aFRR alone were insufficient, mFRR and RR were activated after 15 min. The system frequency was fully restored to 50 Hz in approximately 31 min.

These results demonstrate that the proposed reserve dimensioning and activation sequence ensure compliance with CE requirements, keeping the frequency within the critical 49.2 Hz limit. Under the most severe case (600 MW loss), the system frequency does not remain above the CE critical threshold of 49.2 Hz, and recovery extended to 36 min.

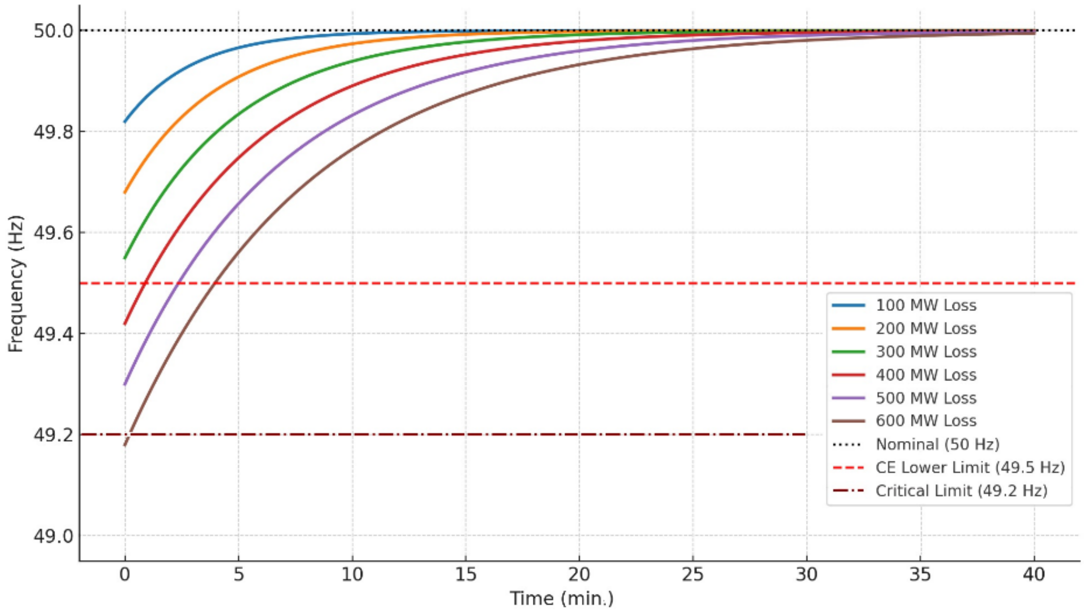

Figure 5. Frequency response under different disturbances.

7.2. FRCE Performance Evaluation

Figure 6 presents the FRCE over a simulated 24-h period. The results indicate that FRCE remained within the Level 1 threshold (±80 MW) for over 75% of the time, surpassing the 70% compliance requirement set by SOGL. Moreover, FRCE exceeded the stricter Level 2 limit (±150 MW) for less than 4% of the intervals, thereby meeting the 5% maximum exceedance criterion. This confirms that the system not only fulfills the regulatory quality targets but also exhibits robust dynamic performance under varying load and generation conditions.

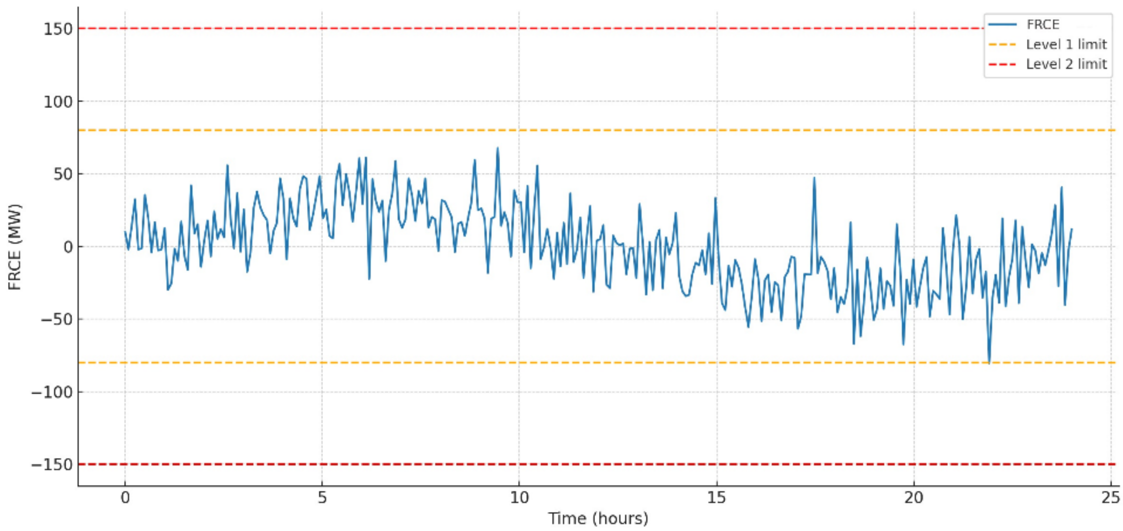

Figure 6. FRCE performance over 24 h.

Simulation results demonstrate that the EPS maintained FRCE within the SOGL-defined target range for more than 75% of the simulated operational time, thereby exceeding the minimum compliance threshold of 70%. Moreover, in critical disturbance scenarios, FRCE values did not surpass the stricter level-2 limit for more than 4% of the time intervals, thus also meeting CE quality standards.

Together, these simulation outcomes validate the effectiveness of the proposed LFC and reserve prequalification framework. They show that the EPS can withstand moderate and severe disturbances while maintaining frequency stability, meeting SOGL performance criteria, and ensuring operational reliability during synchronization with CE.

The model also confirmed the reliability of LER units, provided that ERM strategies were in place. In stress-test scenarios, LER resources successfully contributed to frequency restoration without depleting their reservoirs, thereby validating the prequalification criteria that require providers to specify operational constraints and replenishment strategies.

The results confirm that the proposed LFC framework and harmonized prequalification procedures ensure compliance with CE requirements, while guaranteeing stable and reliable EPS operation under both moderate and severe disturbances.

8. Discussion

The results highlight the importance of coordinated system management, not only at the technical level but also in terms of daily operational practices across different regions. By harmonizing prequalification procedures and reserve activation principles, TSOs in various countries will be able to operate under a common framework, thereby ensuring a level playing field for BSPs. In practice, this means that reserve providers in smaller or less interconnected regions will face the same requirements as those in larger systems, potentially increasing competition while simultaneously raising the bar for technical compliance. For daily operations, such harmonization facilitates smoother cross-border exchanges, more efficient reserve sharing, and improved transparency in balancing markets.

However, several implementation challenges remain. One of the key obstacles is the heterogeneity of existing infrastructures across different EPSs. Some regions may require significant investment in control and communication systems to fully comply with the SOGL-defined monitoring and reserve activation requirements. Another challenge is the integration of LER providers, which necessitates robust ERM strategies to avoid depletion during extended disturbances. Additionally, institutional and regulatory alignment across national authorities may slow down the full implementation of standardized procedures.

At the same time, the proposed framework offers opportunities for further optimization. Increasing the use of automated and data-driven reserve management could enhance real-time balancing efficiency, particularly through predictive algorithms that anticipate system imbalances. Greater reliance on distributed resources such as demand-side response and storage could also improve flexibility, provided that prequalification procedures evolve to accommodate these emerging actors. Furthermore, joint regional testing and simulation exercises could reduce redundancy, streamline approval processes, and accelerate readiness for CE synchronization.

While the coordinated LFC and reserve prequalification system ensures compliance with CE standards, its practical success will depend on the ability of TSOs and BSPs to overcome implementation barriers and to exploit technological advancements that enable more flexible and efficient balancing in daily operations.

9. Conclusions

This study has shown that a harmonized LFC framework and standardized prequalification procedures are essential to ensure reliable EPS performance during synchronization with CE. Simulation results validated with real-world operational data confirm that the proposed approach maintains frequency stability under different disturbance scenarios and meets the SOGL performance targets.

To translate these findings into practice, several actionable recommendations emerge: (1) Strengthen infrastructure readiness: TSOs should prioritize investments in advanced monitoring, communication, and control systems to guarantee reliable reserve activation across regions; (2) Enhance prequalification procedures: regular, transparent testing of BSPs, including LER providers, must be enforced to ensure compliance and operational resilience; (3) Promote regional cooperation: coordinated reserve dimensioning and cross-border simulation exercises should be institutionalized to minimize redundancy and improve interoperability; (4) Leverage advanced tools: the adoption of predictive analytics and auto-driven control strategies can further optimize reserve activation, particularly under high renewable penetration; (5) Foster regulatory alignment: policymakers should harmonize national requirements with CE standards while allowing flexibility for integrating distributed resources such as demand response and storage.

Despite its strengths, this framework is still constrained by its reliance on simulation studies, which may not fully capture real-world complexities. Future work should include pilot implementations in live EPS environments, more detailed modeling of distributed resources, and long-term assessments of market integration impacts.

The proposed framework offers a robust pathway for CE synchronization. By combining technical harmonization, coordinated operation, and forward-looking innovation, it provides both immediate operational reliability and a foundation for the future evolution of European power system integration.

Author Contributions

Conceptualization, R.D.; methodology, R.R.; software, K.O.; validation, M.K.; formal analysis, R.D.; investigation, K.O. and R.R.; resources, M.K.; data curation, R.D.; writing—original draft preparation, K.O., R.D., and R.R.; writing—review and editing, K.O., R.D. and M.K.; visualization, M.K.; supervision, R.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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