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ENHANCING FREQUENCY CONTAINMENT RESERVE MONITORING USING PHASOR MEASUREMENT UNITS

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Abstract: In an increasingly dynamic power system with growing integration of renewable energy sources, real-time monitoring of primary frequency regulation—or Frequency Containment Reserve (FCR)—is essential for maintaining system stability and operational reliability. This paper presents a comprehensive approach to FCR monitoring based on high-resolution, time-synchronized measurements provided by Phasor Measurement Units (PMUs), with a focus on hydropower plants as primary FCR providers due to their flexibility and rapid response capabilities. The need for accurate and granular FCR monitoring arises from the limitations of traditional SCADA-based systems, which often lack sufficient temporal resolution and synchronization to capture dynamic frequency response behaviour. By contrast, PMUs enable precise tracking of frequency deviations, generator reaction times, and control characteristics such as droop and deadband. This enables a signal-based evaluation of each unit's contribution to FCR, offering valuable insights into underperformance, delays, or asymmetric responses. However, signal analysis alone is not sufficient to fully evaluate FCR compliance. Therefore, the proposed monitoring framework integrates PMU-based detection performed within the WAMSTER platform with operational data collected from generating units via the PI AVEVA system. While WAMSTER verifies actual frequency response using synchrophasor data, PI AVEVA provides contextual information including production schedules, temporary limitations, and technological constraints. Based on this data, the expected FCR contribution is calculated for each unit, allowing for a comparison between expected and actual response. The monitoring architecture is realized through standardized protocols: IEEE C37.118 for real-time synchrophasor exchange between WAMSTER and PI AVEVA, and IEC 60870-5-104 for communication between local plant systems and PI AVEVA. The result is a scalable and modular system capable of providing system operators and analysts with an integrated, data-driven platform for comprehensive FCR evaluation and reporting. This paper outlines the development of the monitoring solution, including the design of the application, integration of PMU and plant data, and a case study focused on hydropower implementation. The findings highlight how combining PMU technology with contextual operational data provides a more complete understanding of FCR delivery, improves transparency, and supports compliance with regulatory requirements in modern, decarbonizing power systems.

Keywords: synchrophasors, FCR, primary frequency control

INTRODUCTION

Maintaining frequency stability is one of the fundamental challenges in modern power systems. With increasing penetration of renewable energy sources and a more dynamic grid environment, ensuring a fast and reliable response to frequency deviations is critical for grid stability. Primary frequency regulation, also known as Frequency Containment Reserve (FCR), plays a key role in automatically correcting imbalances between generation and consumption by adjusting power output in real-time. Unlike secondary frequency regulation (aFRR), which is centrally controlled by the TSO to restore frequency to its nominal value over a longer period, FCR operates autonomously based on local frequency deviations and provides an immediate response to stabilize the grid. FCR is typically delivered by generating units operating in Frequency Sensitive Mode (FSM). These units autonomously adjust their active power output in proportion to the measured frequency deviation, according to a defined droop characteristic and within a set deadband. The power-frequency response follows a linear droop function:

$$\Delta P = \frac{\Delta f}{s} \cdot P_{nom} \quad (1)$$

where ΔP is the change in active power, Δf is the frequency deviation forma nominal (in Hz), s is the droop setting (as per unit or percentage value) and P_{nom} is the nominal power of the unit.

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Traditionally, FCR monitoring has relied on SCADA-based systems and direct communication between power plants and system operators. However, these methods often suffer from low data resolution, delays, and limited synchronization, making it difficult to precisely assess frequency response dynamics. With the advancement of Phasor Measurement Units (PMUs), a new approach to high-resolution, time-synchronized FCR monitoring is emerging. PMUs allow for real-time assessment of generator response, deadband effects, and system-wide frequency behavior—all without requiring direct signal exchange between the system operator and the power plant. This paper explores the concept of primary frequency regulation, the evolution of FCR monitoring, and the application of PMU-based technologies to improve real-time monitoring. Additionally, the development of a PMU-based monitoring application and a case study on its implementation in hydropower plants will be presented. The findings highlight how PMU technology is transforming FCR monitoring, enhancing grid stability, compliance verification, and operational efficiency in modern grids.

1. PRIMARY FREQUENCY REGULATION AND MONITORING REQUIREMENTS

1.1. Definition and role of FCR in power systems

In normal operation, frequency deviations from the nominal value occur due to fluctuations in electricity consumption and generation. The dynamics and magnitude of these changes allow the frequency to remain within relatively narrow limits around the nominal value, provided that the interconnected system has sufficient power reserves (i.e., regulatory reserves) to compensate for both upward and downward frequency variations. These regulatory reserves must be activated swiftly enough to match the dynamics of these fluctuations and promptly correct any system imbalances.

The process of maintaining frequency within the desired limits is known as Frequency Containment, and the regulatory reserve used for this purpose is referred to as the Frequency Containment Reserve (FCR). Traditionally, this type of regulation is known as primary frequency regulation. The activation of the primary reserve follows a two-tier response mechanism:

- 0% to 50% of the reserve must be activated within 15 seconds
- 50% to 100% of the reserve must be activated within a maximum of 30 seconds, following a linear activation profile

The required magnitude of the FCR response is determined by the droop characteristic of the unit, which defines the proportionality between the frequency deviation and the change in active power output:

$$\Delta P_{FCR} = P_{BASE} \frac{\Delta f}{s} \qquad (2)$$

Where ΔP_{FCR} is the change in power due to FCR activation (in MW), P_{BASE} is the base power level or available capacity for regulation, Δf is the frequency deviation forma nominal (in Hz) and s is the droop setting (as per unit or percentage value).

Generating units must comply with specific technical requirements for droop (e.g. adjustable between 2–5% for hydro units), deadband width (typically ±20 mHz) and insensitivity thresholds. These parameters define how precisely and how early the unit begins to respond to a frequency deviation.

The primary frequency regulation service is provided by generating units specifically equipped to operate in Frequency Sensitive Mode (FSM) with minimal insensitivity. This means that these units can continuously adjust their active power output upward or downward depending on both the magnitude and direction of the frequency deviation, while remaining within their declared power regulation limits. Since units operating in FSM must also be capable of increasing their power output in response to a frequency drop in the system, their planned operational load (baseline active power based on the dispatch schedule) must be lower than their maximum continuous power output (Pmax) by an amount equivalent to the required primary frequency reserve. This creates a potential trade-off between maximizing electricity production (full utilization of installed capacity) and ensuring a permanently available regulatory reserve for frequency containment. To address this, the specification of requirements must clearly define the frequency deviation thresholds at which generating units engaged in FCR must fully activate their reserved power capacity for primary regulation. By agreement, this threshold has been set at ±200 mHz from the nominal frequency.

Figure 1 illustrates the various types of frequency maintenance services, highlighting key observations:

- Symmetrical frequency response with minimal deadband (FSM) contributes to frequency correction for deviations greater than $|\Delta f|$ = 200 mHz, maintaining the same droop characteristic as for smaller frequency deviations.
- If the rate of frequency change is slow enough, a generating unit in FSM will fully engage its reserve when the frequency deviation reaches $|\Delta f|$ = 200 mHz. It will continue modulating power output to correct frequency deviations as long as its output remains within the operational limits (Pmin, Pmax), as illustrated by the dashed area in the bottom-right graph.
- The deadbands for LFSM-O and LFSM-U modes do not necessarily have to be identical.

- If a generating unit is designed and configured for a combined limited frequency response (symmetrical) LFSM-O + LFSM-U, it is expected that the deadband will also be symmetrical.

In normal interconnected operation, each control area must contribute proportionally to the total required FCR reserve, based on its share of the total generation. In islanded operation or isolated subsystems, FCR must be capable of fully compensating for the loss of the largest generation unit, preventing frequency from dropping below 49.2 Hz. The monitoring of FCR performance must therefore assess:

- whether the unit activated its full reserve as required,
- the symmetry and speed of the response,
- the presence and impact of deadband or non-linearity,
- compliance with response timeframes (15s/30s activation rule),
- and the actual versus expected power change based on unit droop

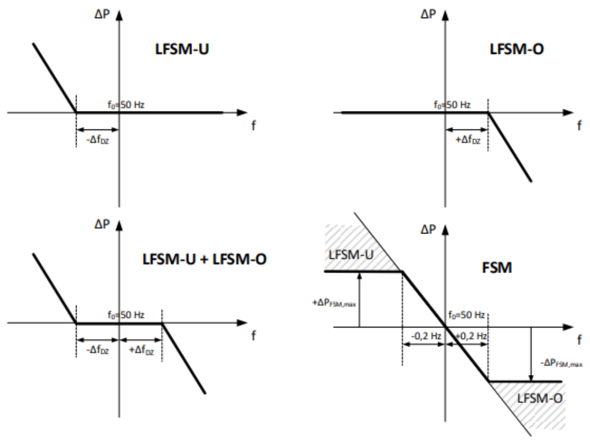

Figure 1: Various types of frequency maintenance services

1.2. FCR monitoring requirements

After establishing the fundamental role of FCR in maintaining grid stability, the next critical aspect is understanding how FCR performance is monitored in power systems. Historically, FCR monitoring has been conducted using SCADA systems and direct communication between power plants and system operators. This method relies on periodic data collection from frequency meters and power plant controllers, which transmit real-time power output and frequency response data to the TSO. This approach comes with several limitations:

- SCADA systems typically collect data at intervals of 2 to 10 seconds, making it difficult to capture fast transient frequency events and analyse the true dynamic response of generating units,
- Dependence on signal exchange: monitoring FCR traditionally requires constant communication between the power plant and the system operator,
- Conventional monitoring systems often lack precise time synchronization between different generating units, making it challenging to accurately compare frequency response behaviour across multiple locations.

These limitations have driven the need for more advanced monitoring solutions that can provide higher resolution, real-time data without requiring constant direct data exchange between system operators and power plants. Modern FCR monitoring must address several key requirements to ensure compliance, transparency, and operational insight:

- It must detect whether the unit delivered the required power response based on its droop setting and frequency deviation.
- The timing of the response must be verifiable, with clear confirmation that at least 50% of the reserve was activated within 15 seconds, and 100% within 30 seconds.
- The system must detect asymmetry, delay, deadband impact, and deviation from expected behaviour.
- The monitoring solution must incorporate both signal-level detection and contextual data such as plant availability, temporary limitations, and operating mode.

To determine the expected FCR contribution at any moment, the relation (2) is used. Consequently, accurate FCR monitoring requires synchronized, high-frequency data as provided by PMUs, along with plant-side metadata accessible through systems like PI AVEVA. These elements, when integrated, provide a complete and reliable view of FCR delivery across the system. Full compliance with SOGL Article 154(8) is foreseen in subsequent development phases, as the outlined approach forms a scalable foundation that can be expanded to meet all regulatory and technical requirements in future iterations of the monitoring solution.

2. PMU BASED FCR MONITORING ARCHITECTURE

2.1. PMU-based signal detection

With the increasing complexity of modern power grids, PMUs have emerged as a transformative technology for real-time, high-resolution monitoring. Unlike traditional monitoring systems that require continuous communication between the power plant and the control center in the TSO, PMUs provide all the necessary data for FCR performance assessment without interfering with the plant's control systems. Figure 2 shows minimal set of high-resolution data nececary for FCR monitoring – frequency and active power captured on high-voltage side of block transformer in 20 ms resolution.

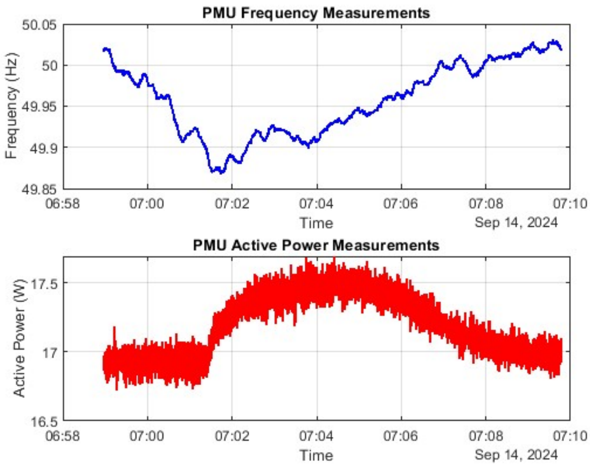

Figure 2: High resolution PMU data

The advantage of this approach is a significant reduction in the time required for system implementation, the avoidance of costs associated with the development, integration and maintenance of specific hardware and/ or software components in each facility, and the easy replication of the system across multiple monitored points. The core functionality of the Phasor Data Concentrator (PDC) must be enhanced with a new software module for verifying the correctness of primary frequency regulation. In its basic implementation, this module must:

- Be synchronized with changes in the power plant's operating setpoint
- Be synchronized with frequency variations to accurately determine the droop curve and confirm that the rate of power increase/decrease and the time required for full engagement of primary frequency reserves comply with the allowed timeframes specified in the relevant technical specifications
- Operate solely based on measurements taken on the high-voltage (HV) side of the step-up transformer
- Have access to the properties of the monitored control loop to validate its correct operation (i.e. droop, deadband..)
- Include filtering capabilities to eliminate oscillations that may occur intermittently or persistently and negatively impact the accuracy of the performance assessment.

The actual response of the generating unit is compared a reference model, which accounts for the unit's characteristics and the desired response behavior. Both the primary and secondary regulation components are evaluated within this framework to ensure compliance with expected performance criteria.

2.2. Integration with plant data

While PMUs enable high-resolution detection of whether a generating unit responds appropriately to frequency deviations—thus indicating its participation in FCR this signal-based assessment alone does not provide a complete picture. In practice, several operational and technical factors at the plant level must be considered to accurately evaluate FCR delivery. This contextual information is essential for interpreting whether deviations from expected FCR behavior are justified.

To that end, complementary data from the power plant is collected via the PI AVEVA system, including information on temporary limitations (e.g., maintenance states, unit availability), technological constraints (e.g., hydraulic or thermal ramping limits), and current operating modes. PI AVEVA, formerly known as OSIsoft PI System, is a real-time data infrastructure platform used for collecting, storing, analyzing and visualizing operational data in industrial environments. It enables the integration of high-frequency data streams with standard SCADA systems and provides tools for advanced monitoring, event detection and visualization.

This integrated approach, combining PMU-based detection with operational data, enables a comprehensive, data-driven evaluation of FCR compliance. It not only ensures accurate performance monitoring but also supports system analysts in identifying deficiencies, justifying non-performance and improving regulatory accountability. In addition, the expected FCR contribution is calculated based on the unit's production plan, droop settings, and the available upward or downward power margin compared to scheduled output. The WAMSTER system then uses PMU data to check whether the unit delivered the expected response during frequency deviations.

The implementation of the requirements specified in the previous chapter is currently underway on the WAMSTER PDC system, operating within the Croatian Transmission System Operator (HOPS) National Control Center. Given the limited experience with monitoring FSM operation—both within HOPS and among FCR providers—it was clear from the outset that, in the first phase of module development, special attention needed to be given to archiving and rapid visualization of recorded responses from monitored units. In the second phase, algorithms for evaluating the performance of primary frequency control will be refined based on insights gained from the analysis of real system recordings.

2.3. Architecture and communication protocols

In the final stage of the monitoring system development, the full integration of signal-based analytics and plant-level operational data is realized within the PI AVEVA environment. While the WAMSTER platform is responsible for detecting whether a generating unit is actively participating in FCR—based on the analysis of high-resolution PMU data—the PI AVEVA system

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provides the centralized framework for combining this information with contextual plant data. This includes production schedules, operating limits, and temporary constraints which are essential for interpreting the measured frequency response in relation to what was expected. The two systems are interconnected using standard communication protocols: synchrophasor data is exchanged between WAMSTER and PI AVEVA via the IEEE C37.118 protocol, while operational signals from generating units are transmitted to PI AVEVA through communication gateways using the IEC 60870-5-104 protocol.

Within this architecture, depicted in Figure 3, PI AVEVA acts as the central platform for data aggregation, real-time visualization, and reporting. It enables analysts and operators to view the actual frequency response of units alongside the calculated expectations and to assess compliance in the context of technical and operational conditions. By unifying signal-based detection and plant-level data in a single environment, the system supports comprehensive, transparent, and scalable FCR monitoring. The PI AVEVA system acts as the central platform that:

- Collects operational signals from generating units
- Receives PMU-derived FCR detection results from WAMSTER
- Provides visualization, alarm logic and reporting tools for system analysts

This architecture ensures a robust and modular FCR monitoring solution, combining high-resolution analytics with centralized plant monitoring and reporting capabilities.

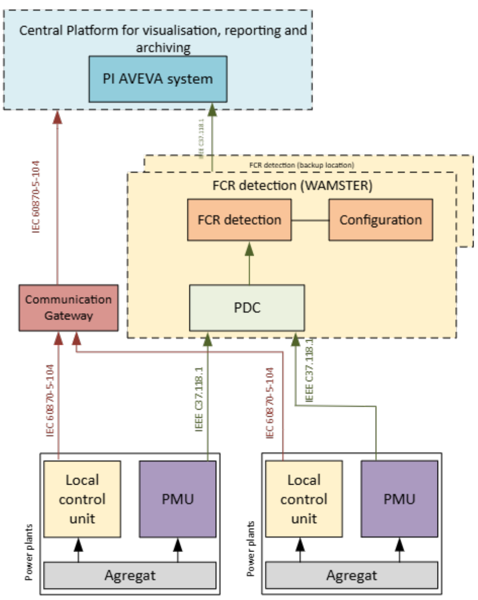

Figure 3: FCR monitoring system architecture

The visualization tools of the WAMSTER system enable a comprehensive data overview using trend and x-y displays. Both can be used for a quick assessment of whether a generation unit responds to frequency deviations, but confirming whether the unit's response aligns with expected or contracted behaviour is complex and time-consuming.

To facilitate this, a generator configuration panel for entering key generator parameters such as rated power, droop, dead zone, insensitivity zone, regulation contribution limits and was implemented. The generator is assigned ID of the PMU device installed on the high-voltage side of the block transformer. Figure 4 illustrates the panel for generation units subject to FCR monitoring. The comparison of expected and recorded characteristics is plotted from a list of previously detected frequency events or from an arbitrarily selected time interval. In the f-P trend diagram of Figure 5, the system frequency (yellow) and generator power (blue) at the PCC are displayed, along with 50% and 100% of the expected regulation contribution delayed by 15 s (red) and 30 s (green), respectively. Those lines defines the minimum response boundary that must be achieved. The f/P diagram shows the P(f) function and the generator's FCR activation characteristic.

Both diagrams are referenced to the generator's active power setpoint, which serves as the pivot point for the diagram. Previous pilot projects on primary frequency control monitoring in the Croatian Transmission system operator HOPS [2,3] have confirmed that estimating the power setpoint at the Point of common coupling (PCC) using PMU devices is easier to implement and replicate than establishing links to generator controllers. Moreover, this approach provides an independent assessment of the delivered FCR activation, unaffected by incorrect controller settings or erroneous data on the generation unit's operating mode. The drawback of this method is its inadequacy in variable conditions, such as during hourly schedule changes, due to feedback effects from nearby generators, or when the unit participates in secondary frequency control.

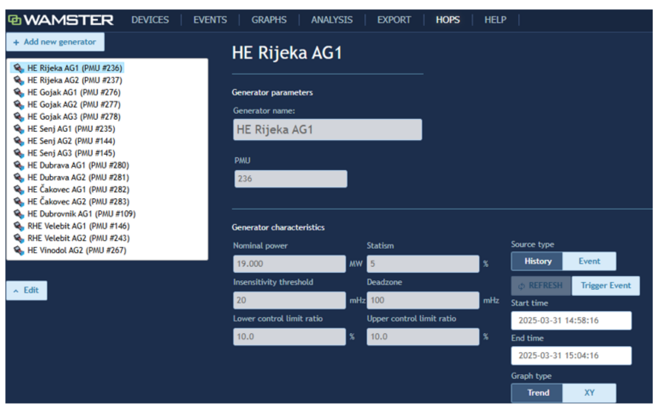

Figure 4. generator selector with generator configuration panel

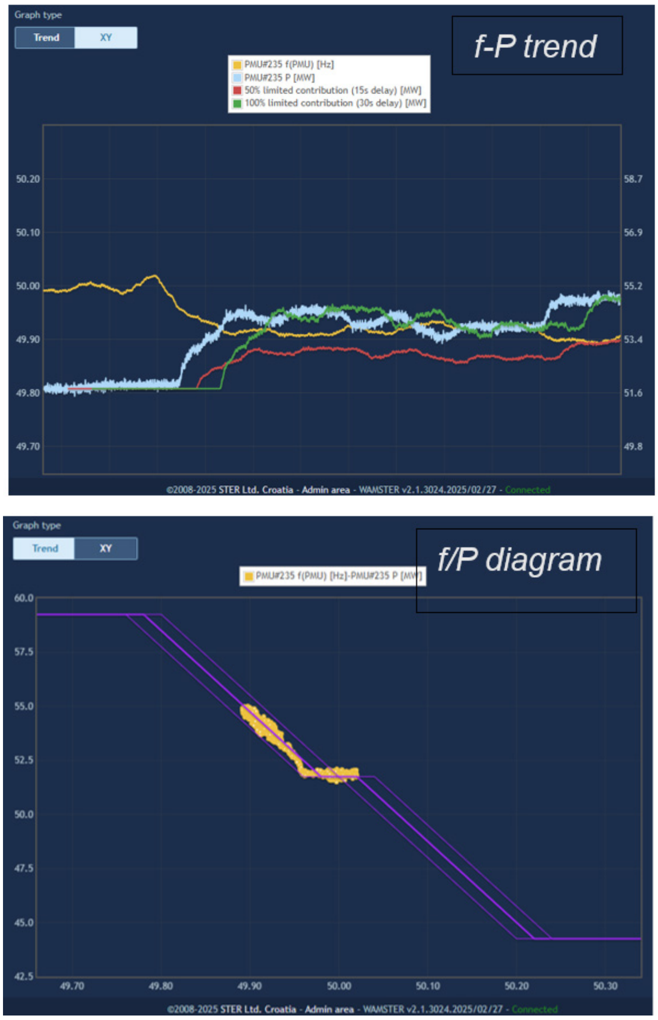

Figure 5: Typical generator FSM response

FSM operation assessment relies on network frequency deviations occurring during normal grid operation. Particularly interesting are deviations greater than 100 mHz, which exceed the dead zone threshold of some generators. Such deviations occur several times per week but generally coincide with scheduled generator dispatch changes. Due to the significant change in power, it is difficult to accurately determine the power setpoint. Furthermore, the small contributions of the FSM algorithm are overshadowed by the significant changes in the generator's operating point and can't be assessed. Therefore, continuous monitoring evaluates responses to smaller frequency variations of around 50 mHz, which occur unrelated to hourly dispatching. Variations below this threshold are unsuitable for analysis due to the low ratio of FSM contribution to noise in the measured power at the PCC.

2.4. Prequalification procedure and monitoring module

As part of the activities to ensure sufficient FCR, HOPS conducts a formal prequalification testing procedure. This process is governed by a predefined protocol that simulates grid frequency feedback and monitors the unit's power at the PCC. The procedure includes recording static and dynamic characteristics of the unit in response to step frequency changes [4].

Static characteristic test

The static test evaluates the steady-state response of the generating unit to a series of step changes in frequency. In this phase, the reference frequency is shifted by increments of ±50 mHz from nominal (50 Hz), covering the range from −300 mHz to +300 mHz. Each frequency level is maintained for 5 minutes to ensure the system reaches steady state. The resulting active power output is used to confirm that the unit's power-frequency characteristic matches the expected droop behavior, as illustrated in Figure 1.

Dynamic charactestic test

The dynamic test assesses the unit's time-domain response to frequency events. Step deviations of ±100 mHz and ±200 mHz are introduced, and the timing of the unit's power response is evaluated. According to FCR requirements, the unit must reach:

- at least 50% of its total FCR response within 15 seconds,
- and 100% of the response within 30 seconds.

This part of the test is critical to confirm compliance with response speed obligations.

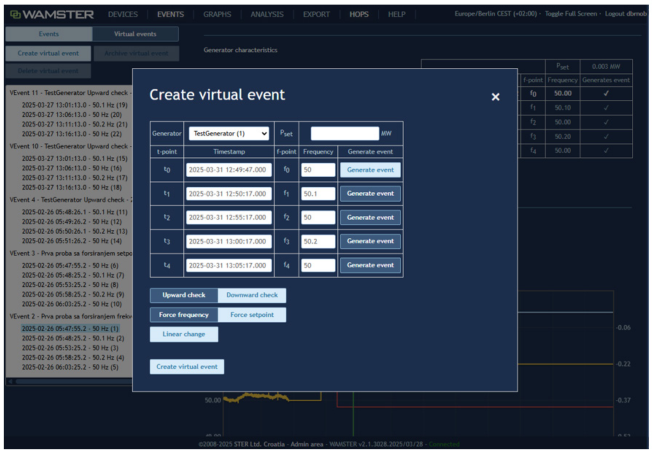

Figure 6: The prequalification procedure setup form

Digital prequalification module

To support and automate the evaluation of these tests, a dedicated software module has been developed within the monitoring platform. ts primary function is to assist experts and test witnesses in configuring, analyzing, and documenting the results of the prequalification process. During or after the requalification test is conducted, the tester, expert, or witness enters the timing of the test actions into the prequalification procedure setup form shown in Figure 6. The form also allows the selection of either under-frequency or over-frequency testing direction and the simulation method - either grid frequency simulation or frequency setpoint change. More complex test procedures can be created by increasing the number of steps and selecting linear interpolation between two points.

After confirming test protocol parameters, the corresponding PMU device's f and P readings are retrieved from the historical database. In this step, 4 virtual frequency events are created for over-frequency and 4 virtual events for under-frequency testing response. The frequency readings is retrieved from database and modified according to the selected criterion. The review and evaluation of generator response follow the same process as for real frequency events but based on the modified frequency value. The final step in the documenting of the dynamic responses of the prequalification process for providing the FCR service is the locking of the recorded data, their permanent archiving and export to a separate repository.

3. CONCLUSION

This paper presents a modular and scalable solution for monitoring Frequency Containment Reserve (FCR) delivery using PMU-based detection integrated with contextual plant-level data. By combining high-resolution synchrophasor measurements and expected FCR values derived from production plans and unit constraints, the system provides a comprehensive view of regulation performance.

The monitoring architecture leverages the WAMSTER platform for signal-based detection and PI AVEVA for integration, visualization, and data aggregation. This two-layer approach ensures both technical accuracy and operational relevance. The system's reliance on standard protocols (IEEE C37.118 and IEC 60870-5-104) further supports interoperability and easy deployment across different power plants.

Initial implementation confirmed that PMU-based signal analysis, when enriched with contextual data, provides a reliable method for verifying FCR compliance without interfering with plant control systems. The visualization tools and prequalification modules developed within this framework offer practical support for both real-time monitoring and regulatory reporting. This integrated approach represents a significant advancement in FCR supervision, enabling transparent, efficient, and automated evaluation of regulation performance in an evolving power system environment.

KEYWORDS

Frequency Containment reserve, Phasor measurement unit, real time monitoring

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