TWINVEST
Digital Twin for Forecasting of Power Production to Wind Energy Demand

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D3.4 – GRID CONNECTION REQUIREMENTS FOR ANCILLARY SERVICES

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LIST OF ABBREVIATIONS

ACER	Agency for the Cooperation of Energy Regulators
aFRR	Automatic Frequency Restoration Reserve
AI	Artificial Intelligence
AS	Ancillary Services
BESS	Battery Energy Storage System
CEP	Clean Energy for all European Package
DSO	Distribution System Operator
EB	Electricity Balancing Regulation
EFB	Exclusive Feature Bundling
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage Systems
EU	European Union
FCR	Frequency Containment Reserve
FRT	Fault Ride-Through
GOSS	Gradient-based One Side Sampling
kVAR	Kilo Reactive Power
LFP	Lithium Iron Phosphate
LightGBM	Light Gradient Boosting Machine
LOC	Location code
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Restoration Reserve
ML	Machine Learning
MW	Mega Watts
MWh	Mega Watts Hours
NMC	Nickel Manganese Cobalt
PICASSO	Platform for the International Coordination of Automatic Secondary Reserve
PPC	Public Power Corporation

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PQ	Power Quality
RES	Renewable Energy Sources
RR	Replacement Reserve
SMOTE	Synthetic Minority Over-sampling Technique
TERRE	Trans European Replacement Reserve Exchange
TSO	Transmission System Operator
VAR	Volt-Ampere Reactive
VRT	Voltage Ride-Through
XGBoost	Extreme Gradient Boosting

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1 INTRODUCTION

The transformation of the European energy landscape, driven by the accelerated integration of renewable energy sources (RES), has fundamentally reshaped the dynamics of electricity generation, transmission, and distribution. While the transition toward cleaner and more sustainable energy systems is vital for achieving the European Union's climate goals, it also presents significant challenges in maintaining grid stability, reliability, and operational efficiency. As conventional, dispatchable power plants are increasingly replaced by variable renewable sources, the grid must adapt to fluctuations in supply and demand through more agile and intelligent mechanisms.

Ancillary services play a crucial role in supporting the secure and stable operation of the power system. These services—such as frequency regulation, voltage support, reactive power compensation, and spinning reserves—are essential for ensuring the grid operates within its technical limits, even as generation becomes more decentralized and intermittent. The evolving energy mix calls for more advanced approaches to the planning, provisioning, and management of these services, especially under the constraints of national and regional regulatory frameworks.

Energy Storage Systems (ESS) have emerged as a key enabler of flexible grid operation. By absorbing, storing, and releasing energy on demand, storage technologies can effectively support the delivery of ancillary services. The alignment between storage capabilities and the specific requirements of ancillary services must be carefully assessed to ensure technical feasibility, cost-effectiveness, and regulatory compliance.

At the same time, the digitalization of energy systems, supported by big data and artificial intelligence (AI), offers new opportunities to enhance the predictability, responsiveness, and integration of ancillary services. Data-driven models can help forecast grid disturbances, optimize resource allocation, and support decision-making processes across different levels of the electricity value chain.

This deliverable provides a comprehensive examination of the regulatory, technical, and operational requirements for grid connection and ancillary service provision. It also explores the potential of advanced modelling approaches to support strategic energy storage deployment and improve the overall resilience and flexibility of grid networks across Europe.

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2 REGULATORY REQUIREMENTS FOR ANCILLARY SERVICES IN THE EU

2.1 The role of ancillary services

In the context of transitioning towards a decarbonized energy system, **ancillary services (AS)** ensure the reliable and secure operation of the electricity system. Traditionally delivered by large, centralized fossil-fueled generation units, these services include frequency containment and restoration, voltage control, inertia provision and black start capability. As variable renewable energy sources such as wind and solar power displace conventional generation, the availability, quality, and responsibility of delivering these services must be fundamentally rethought.

The growing penetration of RES presents both opportunities and challenges for power system operators. On one hand, modern wind and solar technologies are increasingly capable of contributing to system stability through advanced power electronics and control systems. On the other hand, their variability, limited inertia contribution, and dispersed geographical deployment demand a re-engineering of both regulatory frameworks and market structures to ensure that these resources can reliably provide ancillary services when needed.

Addressing ancillary services in power systems is crucial for fully unlocking the potential of RES As the energy grid becomes increasingly reliant on RES, such as wind and solar, ensuring grid stability becomes more complex due to the intermittent and variable nature of these energy sources. However, through the integration of advanced technologies and grid management strategies, RES can actively contribute to stabilizing the grid, mitigating risks that would otherwise arise, such as inefficient curtailments, power outages, or even widespread blackouts. Key capabilities like advanced forecasting, synthetic inertia, fast frequency response, and reactive power support enable RES to enhance grid reliability, reducing the need for expensive backup solutions and minimizing system inefficiencies. In recognition of this potential, the European Union has taken significant steps to ensure that RES can play a more substantial role in grid stabilization by adopting various legislative frameworks. To address these challenges, a coordinated and comprehensive assessment of regulatory requirements is essential. Such an assessment would identify inconsistencies, best practices, and opportunities for harmonizing regulatory frameworks across different regions, fostering a more integrated and efficient energy market. Ultimately, overcoming these regulatory barriers would unlock the full potential of RES, ensuring that they contribute effectively to a stable, cost-efficient, and sustainable power system across Europe.

Given these pressing motivations, this chapter seeks to achieve three strategic objectives. First, it aims to analyze and present the current EU-wide regulatory framework for ancillary services, including the role of key legislative instruments like the Clean Energy Package, network codes, and their national interpretations. Second, it seeks to develop a comprehensive mapping of ancillary service requirements and their implementation across all EU Member States, utilizing data collected from Transmission System Operator (TSO) platforms, regulatory reports, and national guidelines. Third, it will

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assess the compliance, readiness, and gaps in the ability of RES to meet current and future ancillary service obligations.

By delivering these insights, this work contributes to a more harmonized, efficient, and resilient energy system where renewables play a central role not only in energy supply, but also in maintaining system balance and security. This chapter is not only a technical and regulatory analysis but also a strategic step toward making the EU power system fit for a high-RES future.

2.2 Overview of EU ancillary service framework

Instruments such as the Clean Energy for All Europeans Package (ENTSO-E, 2019), the Electricity Balancing Guideline (EU, 2017), and the Network Code Requirements for Generators have been introduced to facilitate the integration of RES and ensure their active participation in grid balancing. These initiatives aim to harmonize grid operation standards, promote the development of flexible electricity markets, and enhance the role of RES in ancillary services. However, the implementation of these policies varies across EU member states, leading to a fragmented regulatory landscape. This fragmentation creates challenges for cross-border cooperation and limits the full participation of RES in some markets, reducing the efficiency of the overall European energy system.

2.2.1 Key regulatory policies

1. **Directive (EU) 2019/944** (Emissions-EUETS.com, 2024)
   As stated in Article 2(48) of Directive (EU) 2019/944 of the European Parliament 'ancillary service' means a service necessary for the operation of a transmission or distribution system, including balancing and non-frequency ancillary services, but not including congestion management.
   TSOs procure ancillary services that can be labelled as:
   - Frequency ancillary services which are necessary to balance the system,
   - Non-frequency ancillary services which include for example voltage controls and black-start capability.

   Among these, there are some services that are mandatory and not remunerated and others optional, stipulated by each network code, traded by according market rules.

2. **Clean Energy for All Europeans Package (CEP)** (ENTSO-E, 2019)
   The CEP is a comprehensive legislative package that redefines the roles of system operators and market participants. It mandates that Transmission System Operators (TSOs) and Distribution System Operators (DSOs) procure ancillary services—such as balancing and flexibility—through transparent, market-based procedures. The CEP also emphasizes the importance of DSO-TSO cooperation, particularly in sharing flexibility resources and managing

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associated data. This framework encourages the use of smart technologies and active grid management to accommodate the variability of renewable energy sources.

3. **Electricity Balancing Guidelines Commission Regulation (EU) 2017/2195** (EU, 2017)
   The Electricity Balancing Guideline establishes a harmonized framework for electricity balancing across European Union member states. Its main goal is to enhance the efficiency of balancing markets by promoting cross-border cooperation, integrating balancing resources, and enabling market-based procurement of balancing services (such as Frequency Containment Reserve, aFRR, and mFRR). The regulation defines roles and responsibilities for Transmission System Operators (TSOs), sets rules for imbalance settlement, and introduces platforms like PICASSO and MARI to facilitate standardized balancing energy exchanges. Ultimately, it aims to improve security of supply, cost efficiency, and the integration of renewable energy across the EU electricity system.

4. **Agency for the Cooperation of Energy Regulators (ACERS) Recommendations** (ACER, 2024)
   ACER highlights the need for clear regulatory frameworks to support distribution networks and local markets for distributed flexibility services. Their recommendations stress the importance of improving EU legislation to facilitate the integration of renewable energy and the development of local flexibility markets.

2.2.2 Assessment of ancillary services requirement across EU

Based on national grid codes, ENTSO-E surveys and public information, the main requirements for ancillary services for each EU member state and Turkiye as of interest within the project scope are compiled below.

The frequency ancillary services procured by TSOs include the following:

- Frequency Containment Reserve (FCR): primary frequency control is designed to ensure the operational reliability of power systems by stabilizing system frequency within seconds after a disturbance or incident. Depending on national regulations, this service may be mandatory or acquired through market-based mechanisms, which can vary in terms of compensation models, response times, and minimum capacity requirements.
- Automatic Frequency Restoration Reserve (aFRR): secondary frequency control adjusts the active power output of generating units to restore system frequency and manage power exchanges with other grids following an imbalance. While primary control limits and halts the initial frequency deviation, secondary control returns the frequency to its nominal value.
- Manual Frequency Restoration Reserve (mFRR):tertiary control is a type of power reserve used by TSOs to restore the balance between electricity supply and demand after a disturbance and it is used to restore the primary and secondary frequency control reserves.

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A scheme of the three regulations is shown in the Figure *1 (Díaz-González, Hau, Sumper, & Gomis-Bellmunt, 2014)* .

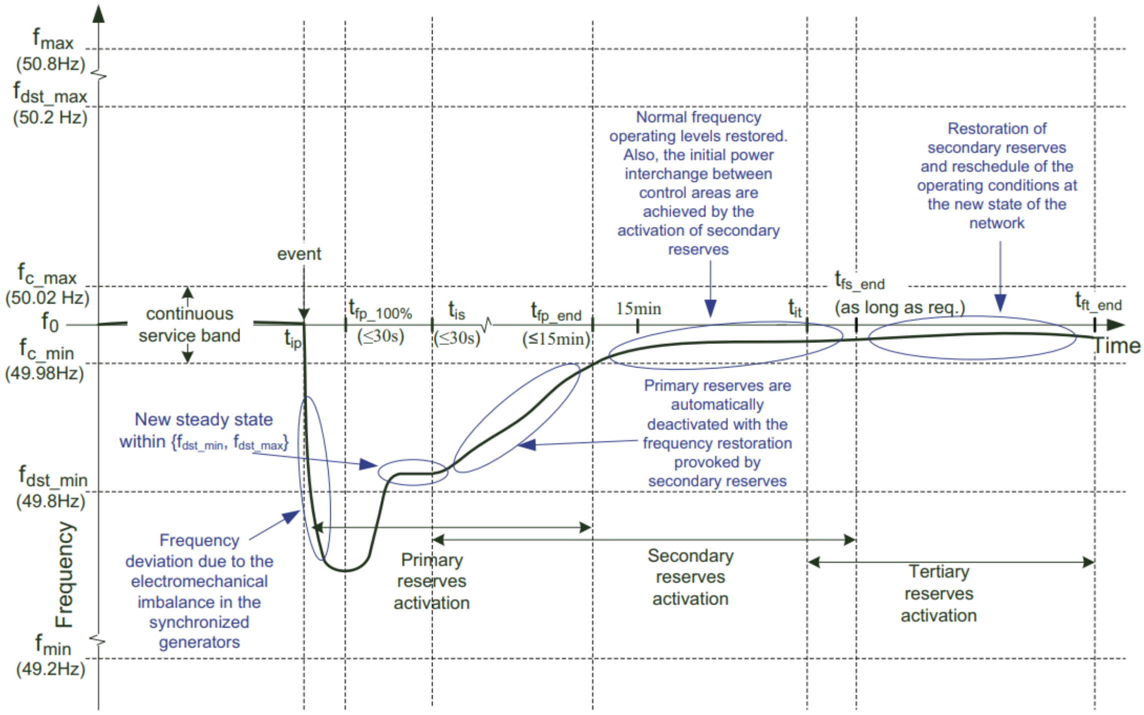

Figure 1 Primary, secondary and tertiary frequency regulation

Figure *2 (ENTSO-E, 2022)* summarizes the requirements for the primary frequency regulation of each country.

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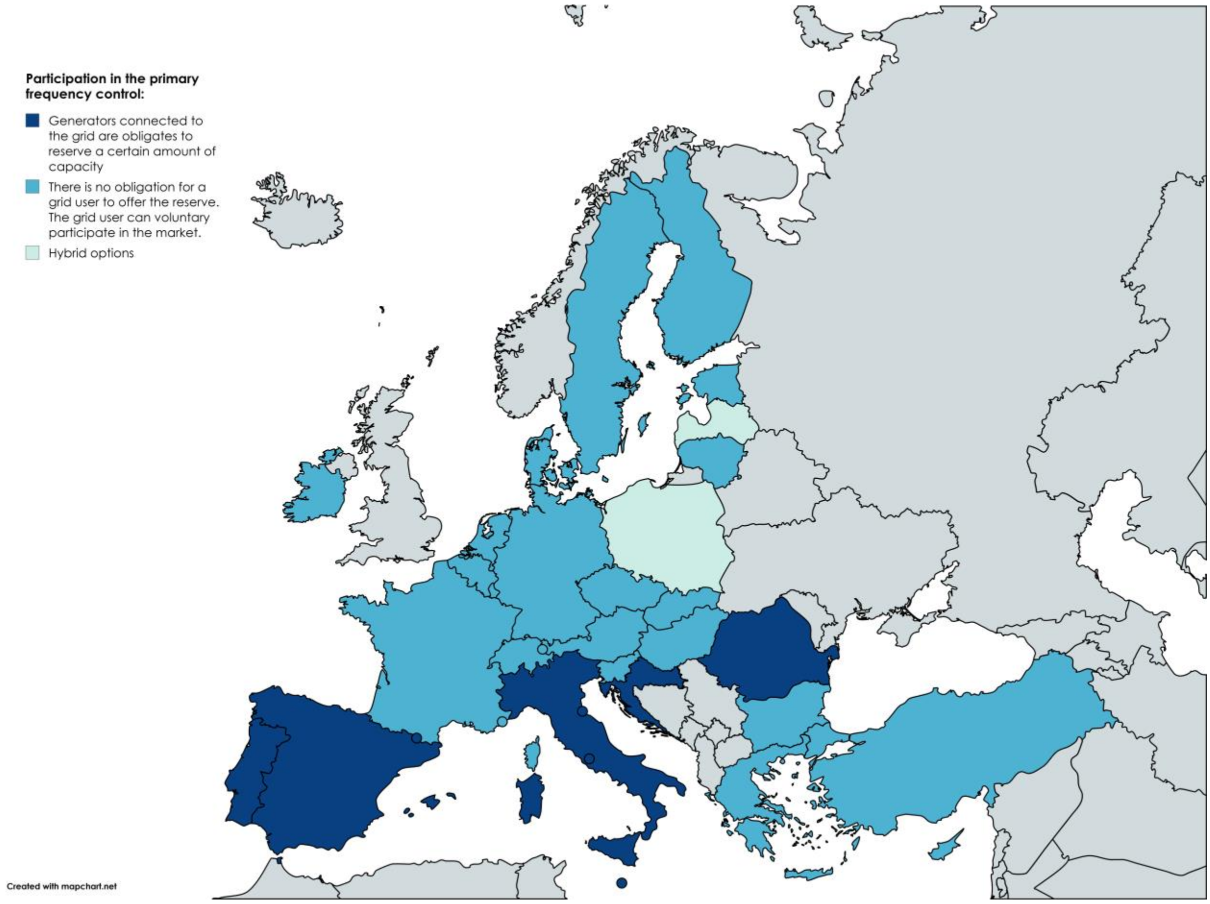

Figure 2 Map of primary frequency regulation requirements of the EU member states and Turkiye

Regarding secondary and tertiary frequency regulation, most available information indicates that market-based solutions are the predominant approach across European countries. Specifically, according to the latest ENTSO-E (European Network of Transmission System Operators for Electricity) survey on ancillary services, France and Croatia require generators to reserve a certain amount of capacity for secondary regulation. In the case of tertiary regulation, Estonia stands out as the only country not employing a market-based mechanism to secure reserve capacity. The specific rules governing these markets vary by country, particularly in terms of the minimum bid size and time resolution, which are defined within each nation's regulatory framework (ENTSO-E, 2022).

Besides the individual requirements, ancillary services are also managed between countries for which TSOs join dedicated platforms for the procurement and the activation of balancing energy.

In particular, the TERRE (Trans European Replacement Reserve Exchange) project is the European implementation project for exchanging replacement reserves in line with EB Regulation (Article 19). The EB Regulation which entered into force on 18 December 2017 provides the technical and operational framework and defines the market rules for governing the functioning of balancing markets.

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The RR platform shown in Figure *3 (ENTSO-E, TERRE, 2025)* is in operation since 2020, and it enables the exchange and optimised activation of a standard product for balancing energy.

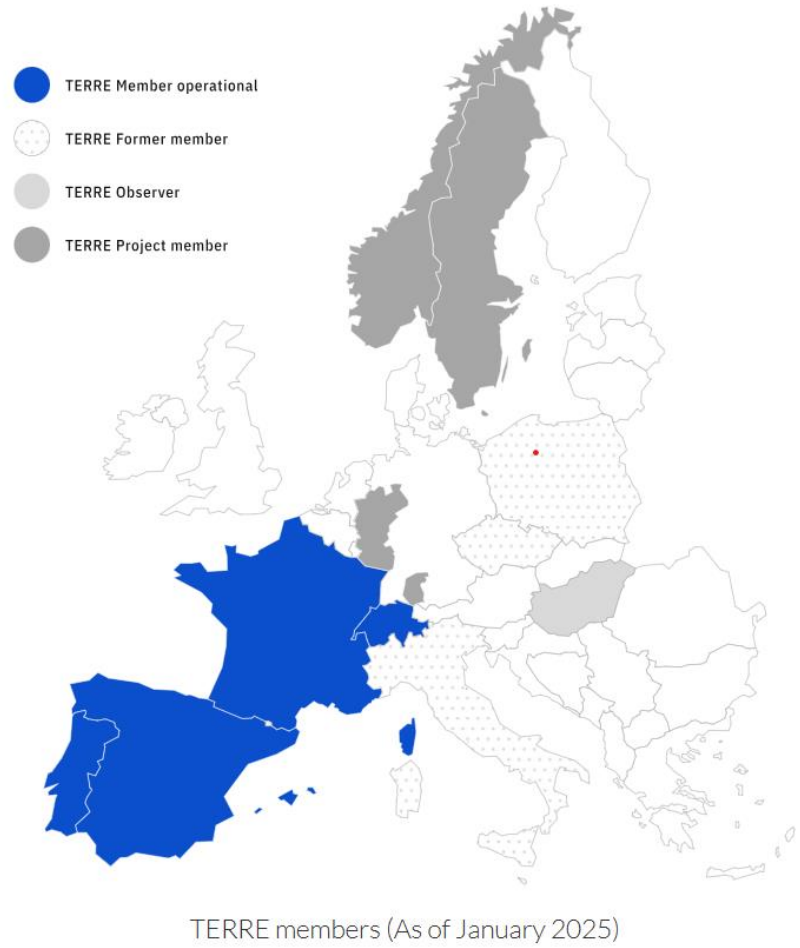

Figure 3 RR platform

Regarding the aFRR service, the European PICASSO project has been responsible for implementing the aFRR platform since 2017. As required in the EB Regulation, the platform is in operations since 2022 shown in Figure *4 (ENTSO-E, PICASSO, 2025)* and it is used from different TSOs to submit balancing energy bids and to exchange aFRR balancing energy bids in order to support their needs.

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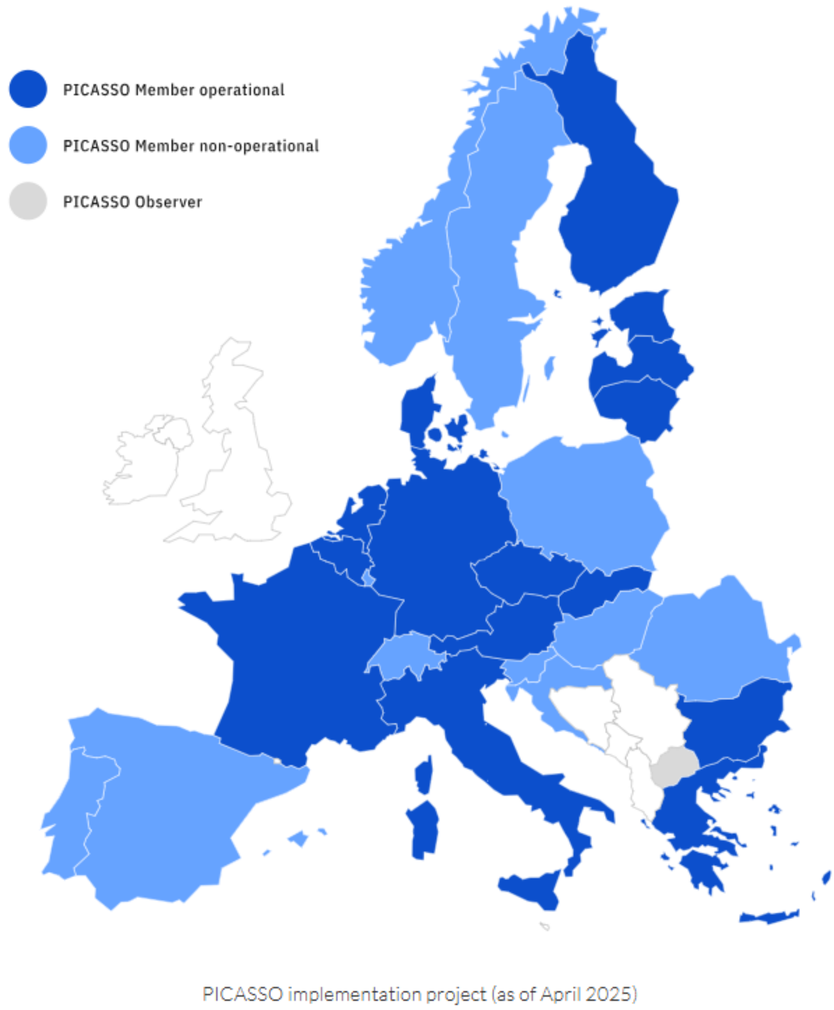

Figure 4 aFRR platform

Moreover, for the mFRR service, a European platform was implemented within the MARI (Manually Activated Reserves Initiative) project, as shown in Figure 5 *(ENTSO-E, MARI, 2024)*.

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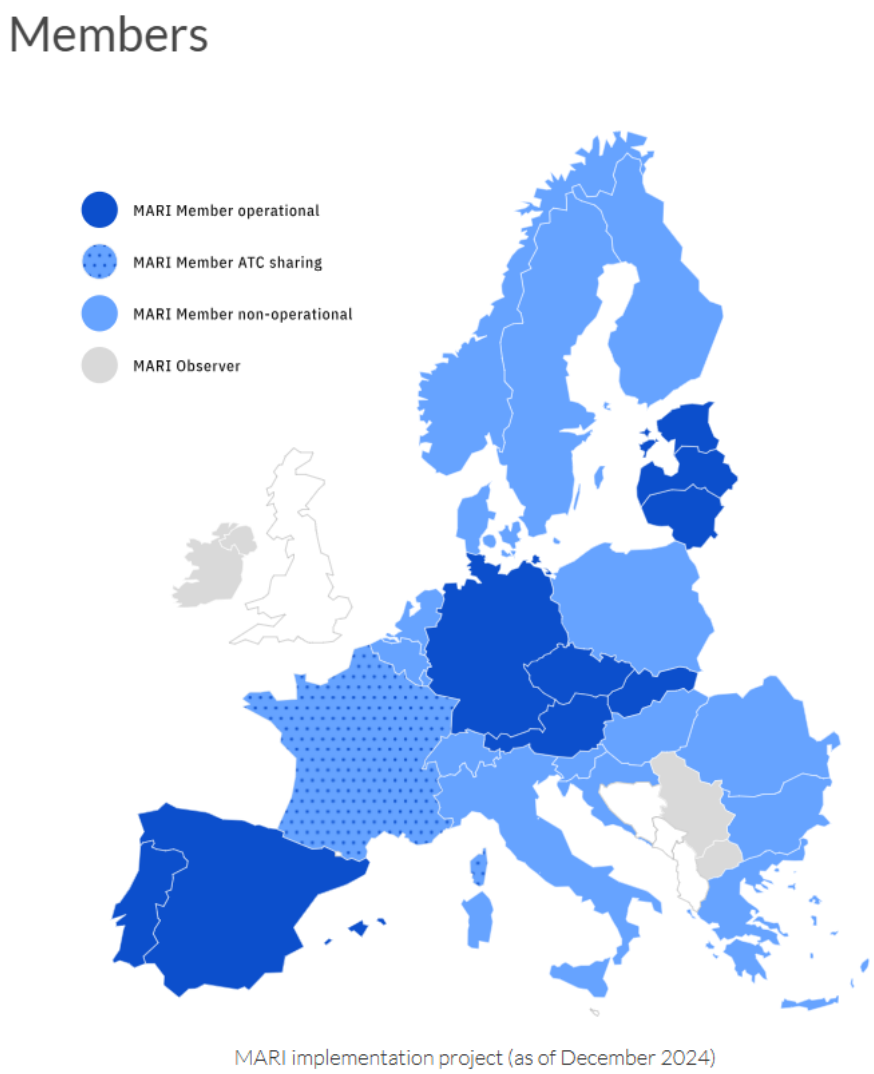

Figure 5 mFRR platform

Among the non-frequency ancillary services procured by TSOs, the followings are included:

- Voltage control: Voltage control refers to the process of managing and regulating the voltage levels within an electrical grid to ensure stable and efficient operation. It involves adjusting the generation and/or absorption of reactive power to maintain the voltage at desired levels, ensuring that it remains within specified limits. Voltage control is vital for preventing over-voltage or under-voltage situations that could damage equipment or disrupt the supply of electricity.
- Reactive power support: Reactive power control is the regulation of reactive power (which does not perform any useful work but is essential for voltage stability) within an electrical grid. It helps maintain voltage levels and ensure that the system operates within safe parameters. By adjusting the amount of reactive power supplied or absorbed by various components, grid

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operators can control voltage profiles, support grid stability, and ensure efficient transmission of active power.

Voltage control and reactive power control are fundamental and mandatory requirements across all European countries to maintain the stability and efficiency of the electrical grid. As part of these efforts, each country's grid code defines specific parameters and limits regarding both voltage levels and reactive power import/export that new plants are required to comply with. These regulations are critical in ensuring that power systems operate within safe and stable conditions, regardless of changes in demand or generation.

In terms of steady-state requirements, grid codes typically specify that voltage levels must remain within defined thresholds to prevent operational issues such as equipment damage or voltage instability. To enforce this, various voltage control mechanisms, such as voltage/reactive power (V/Q) and active power/reactive power (P/Q) curves, are used to determine the appropriate amount of reactive power that needs to be either generated or absorbed to maintain voltage levels within these predefined ranges. The V/Q curve, for example, represents the relationship between the voltage level and the reactive power exchanged, while the P/Q curve maps the balance between active power and reactive power in the grid, ensuring that the system can adjust effectively to varying conditions.

Beyond steady-state requirements, most grid codes also introduce dynamic requirements to address voltage stability during transient events or faults. These dynamic conditions, such as Voltage Ride-Through (VRT) and Fault Ride-Through (FRT), are critical to ensuring the resilience of the grid during disturbances. VRT and FRT requirements stipulate that generating units must remain connected to the grid and continue operating within certain voltage limits during short-term faults or voltage dips. This helps prevent large-scale outages and contributes to the overall stability of the grid during unforeseen events, such as system faults or sudden changes in demand.

Overall, both voltage and reactive power control are essential components for maintaining grid reliability across Europe. By ensuring compliance with these dynamic and steady-state requirements, grid operators can better manage voltage stability, prevent disruptions, and support the smooth integration of renewable energy sources and other generation technologies into the grid.

Furthermore, black-start capability is another ancillary service generally required and procured by the TSOs. The black-start capability consists of contributing to the process of recovering a power station to operation without relying on an external power network. This function is crucial for restoring power after a widespread outage or system collapse, enabling the step-by-step re-energization of the grid. Across Europe, the requirements for black-start capability vary by country but are typically governed by national regulatory frameworks and aligned with ENTSO-E guidelines. TSOs identify specific generating units or technologies capable of providing black-start services based on technical criteria such as rapid self-start ability, islanding operation, synchronization, and load-following capability.

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Some countries mandate black-start readiness from certain types of generators, especially those located in strategic grid areas or those with robust start-up characteristics, such as hydroelectric or gas turbine units. Others procure this service through competitive tenders or bilateral agreements, setting clear technical and operational standards for providers.

Finally, curtailment obligations can be seen as a service for the balancing of the system by dispatching down the power output. It is generally required by the TSO, particularly RES production.

2.3 Compliance assessment

2.3.1 Gaps in ancillary service provisions

A thorough examination of the current requirements on ancillary services among the EU Member States has been conducted with the aim of providing a comprehensive review of the existing standards. However, this research has faced significant challenges due to the fragmented nature of the available information. One of the primary difficulties encountered during the research was the variation in regulatory requirements across European countries. As highlighted in previous sections, not all countries in the European Union have the same grid code regulations or market requirements for RES, leading to inconsistencies and mismatches in the available data.

For instance, some of the most challenging data to obtain were details regarding black start capabilities, particularly the specific needs of various markets. The availability of information on black start, as well as the specific mechanisms by which it is regulated (mandatory or optional), was often vague or absent in the reports reviewed. Similarly, the information available regarding the generation unit was typically generalized and did not focus specifically on the needs and capabilities of wind farms.

Ultimately, the complexity of the subject matter and the fragmentation of available information made it difficult to perform a homogeneous review across the EU. Despite these obstacles, it is clear that a more harmonized approach to regulatory frameworks and market structures is necessary to ensure the efficient provision and integration of ancillary services.

3 DATA GENERATION AND MACHINE LEARNING MODEL DEVELOPMENT

3.1 Synthetic data generation and rationale

In the context of Deliverable D3.4, the development and testing of ML models for grid disturbance detection and classification required access to high-quality, labelled datasets that capture both normal and disturbed grid operating conditions. However, due to the sensitive and proprietary nature of grid operation data, access to historical datasets from Transmission System Operators (TSOs) and Distribution System Operators (DSOs) remains highly restricted. Additionally, available data is often fragmented, lacks consistent labels for disturbance types, or does not cover the full range of disturbances necessary for robust model development. Given these limitations, the generation of a

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synthetic dataset was deemed essential to ensure the continuity of the project's objectives while adhering to data privacy and security considerations.

The synthetic dataset was carefully designed to replicate realistic grid operating conditions observed in European TSOs and DSOs. A probabilistic data simulation approach was adopted, using domain knowledge and industry standards.

Table 1 shows the key operational variables such as voltage, current, frequency, power, and power quality indicators were modelled using normal distributions centered around standard nominal values, with variance introduced to reflect natural operating fluctuations and disturbances. Disturbance events were simulated by deliberately introducing anomalies and deviations in specific variables, reflecting real-world disturbance signatures like voltage sag, swell, frequency deviation, harmonics, flicker, and transients.

The dataset contains 1,000 records, with 30% of entries labelled as disturbance events and 70% as normal operations. The disturbance classes were assigned using weighted probabilities to reflect their typical occurrence frequencies in grid operations. Additionally, contextual factors such as wind speed, solar generation, ambient, and transformer temperatures were included to enhance the dataset's richness and applicability to predictive maintenance and disturbance analysis under varying environmental conditions. Randomization techniques and controlled noise were applied to ensure the data's realism while maintaining its synthetic and privacy-compliant nature. This dataset provides a practical and ethically compliant alternative to real data, enabling the testing, validation, and benchmarking of machine learning algorithms for grid disturbance prediction within the scope of D3.4.

Table 1 Synthetic grid disturbances dataset

Variable Name	Description	Unit	Typical Range	Assumptions
Time stamp	Date and Time of measurement	-	-	5 minute interval
Location ID	Location Identifier	-	Loc_1 to LOC_10	Randomly Assigned
Voltage L1	Phase L1 voltage	V	210 – 250	Normal distribution centered at 230V increased variability in disturbances
Voltage L2	Phase L2 voltage	V	210 – 250	Normal distribution centered at 230V increased variability in disturbances
Voltage L3	Phase L3 voltage	V	210 – 250	Normal distribution centered at 230V increased variability in disturbances
Current L1	Phase L1 current	A	40 – 60	Normally distributed

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Current L2	Phase L2 current	A	40 – 60	Normally distributed
Current L3	Phase L3 current	A	40 – 60	Normally distributed
Frequency	Grid Frequency	Hz	49.5 – 50.5	Normal operation centered at 50Hz; deviations in disturbance events
Active Power	Active power delivered	kW	600 – 1400	Normally distributed
Reactive Power	Reactive power	kVAR	300 – 700	Normally distributed
Power Factor	Power factor	-	0.8 – 1.0	Uniform distribution
Harmonic Distortion	Total Harmonic distortion	%	1.5 – 3.5	Higher values in harmonic disturbances
Voltage Unbalance	Voltage unbalance	%	0.5 – 2.0	Increased during voltage disturbances
Flicker Pst	Short-term flicker severity	-	0.4 – 1.2	Higher in flicker events
Flicker Plt	Long-term flicker severity	-	0.4 – 0.8	Higher in flicker events
Breaker Status	Breaker open/close status	0/1	0, 1	Randomly assigned
Transformer Temperature	Transformer winding temperature	°C	55 – 75	Normally distributed
Ambient Temperature	Ambient temperature	°C	0 – 40	Seasonal variation simulation
Wind speed	Wind speed at location	m/s	2 – 8	Normally distributed
Load demand	Load demand at location	kW	600 – 1200	Normally distributed
Solar generation	Solar generation	kW	100 – 300	Diurnal variation simulation
Event Detection	Event occurrence indicator	0/1	0 (normal), 1 (disturbance)	30% of records labelled as events
Disturbance type	Classified disturbance type	Categorical	Various disturbance classes	Weighted distribution among disturbance classes

3.2 Data generation and preprocessing pipeline

3.2.1 Data Generation

The synthetic data generated in section 3.1 emulates a typical grid disturbance condition encompassing

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- Temporal features: time stamps marking the occurrence of disturbance events.
- Location identifiers: Codes indicating the geographic or grid segment location of the disturbance.
- Disturbance type: categorical classification of various disturbance events.
- Electrical parameters: Measurements such as voltage, current and frequency.

3.2.2 Data preprocessing

A robust preprocessing pipeline was established to prepare the data for ML based grid disturbance prediction.

3.2.2.1 Feature Engineering

- Temporal decomposition:

The timestamp data was decomposed into hour, day_of_week, and month to capture inherent cyclical patterns in grid behaviour and load profiles.

- Categorical Encoding:

Location_ID and disturbance type were encoded using Label Encoder to convert categorical features into numerical format, enabling their utilization in standard machine learning algorithms.

3.2.2.2 Train-Test split

- Stratified Sampling:

The dataset was partitioned into 70% training and 30% testing subsets using stratified sampling to maintain proportional representation of all disturbance types in both sets.

- Reproducibility:

A fixed random state was applied to ensure reproducibility of results.

3.2.3 Handling class Imbalance

Given the inherent imbalance in grid disturbance data (where rare events are underrepresented), Synthetic Minority Over-sampling Technique (SMOTE) was employed:

- Synthetic Sample Generation:

SMOTE synthesizes new minority class instances based on feature space similarities, rather than duplicating existing samples.

- Bias Mitigation:

Balances the dataset to reduce model bias toward majority classes, enhancing recall and sensitivity for rare disturbance events.

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- Overfitting Prevention:

By creating synthetic, rather than replicated, samples, SMOTE supports improved model generalization and mitigates overfitting risks.

3.3 ML Model selection and performance

Accurate and timely prediction of grid disturbances is essential for maintaining grid stability, ensuring reliability, and enabling proactive system management. Given the complexity of grid operations, the rarity of disturbance events, and the high-dimensional nature of the data involved, the choice of appropriate machine learning models becomes critical.

For this study, a diverse set of advanced ensemble learning methods were selected, each offering unique strengths in handling non-linear patterns, imbalanced data, noise, and scalability. The selected models— Random Forest, Gradient Boosting, XGBoost, and LightGBM—are well-established in predictive modelling tasks and have demonstrated robust performance in similar anomaly detection and fault prediction domains.

3.3.1 Random Forest

Random Forest was selected due to its inherent robustness and ability to handle complex, non-linear relationships in power system data. Its ensemble approach, combining multiple decorrelated decision trees through bagging and random feature selection, reduces overfitting while improving generalization—critical for accurately classifying diverse grid disturbances (Chun Zhang, 2016). The model's natural resistance to noise and outliers ensures reliability in real-world scenarios where sensor data may be imperfect. Additionally, its feature importance output provides interpretability, helping engineers identify key indicators of disturbances for proactive grid management.

The Random Forest model demonstrated strong performance by leveraging an ensemble approach that combines multiple decision trees trained on random subsets of the data (bagging) and features, enhancing robustness and reducing overfitting. It achieved the highest accuracy (19.00%) and F1-score (18.00%) among the evaluated models, as shown in Figure 6, indicating effective classification across disturbance types. The model excelled in identifying normal conditions (Figure 7), highlighting its reliability in distinguishing between different operational states. The Random Forest model's confusion matrix demonstrates excellent diagonal dominance, reflecting strong multi-class discrimination capabilities. The ensemble approach shows particularly high accuracy in identifying normal grid conditions (exceeding 90% true positive rate) while maintaining robust performance across various disturbance types. Some symmetrical misclassification patterns appear between complementary events like under-voltage/over-voltage conditions, suggesting the model occasionally struggles with magnitude-direction distinctions. The matrix confirms Random Forest's advantage in handling imbalanced datasets, with consistent performance even for less frequent disturbance categories. The remaining confusion primarily occurs in physically similar events that even expert systems might

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conflate. Its inherent randomness, parallel training, and feature importance estimation contributed to both predictive power and interpretability.

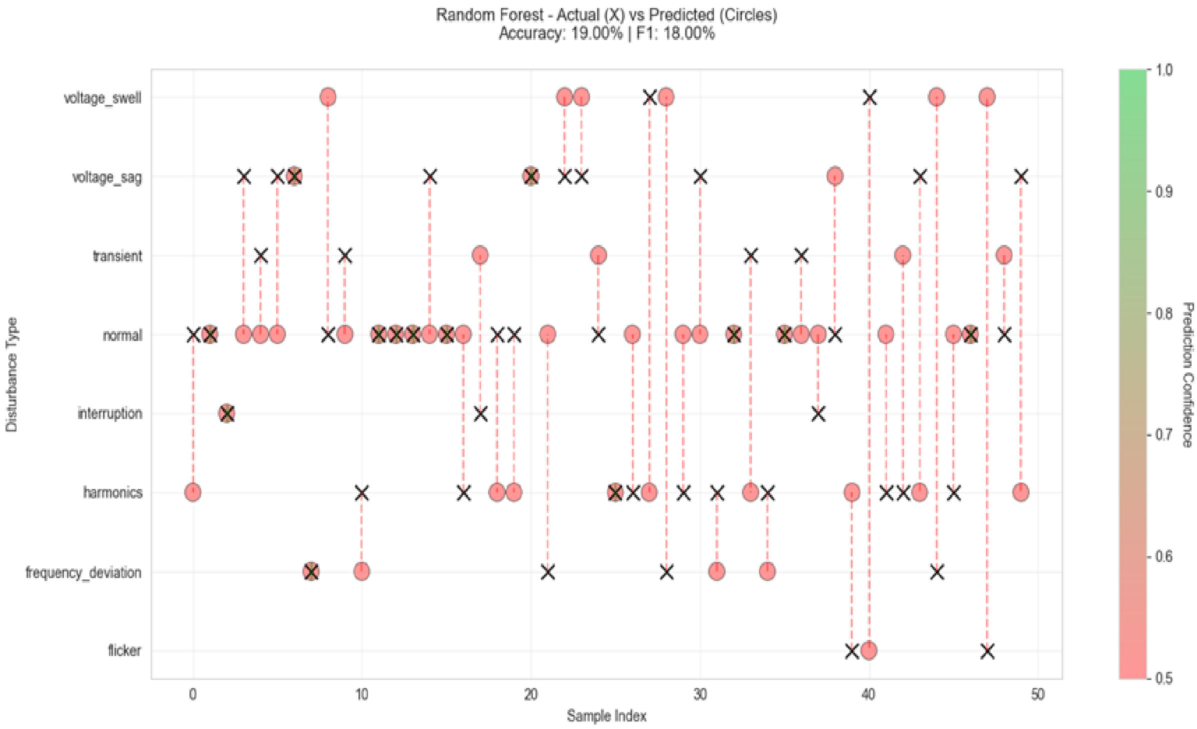

Figure 6 Comparison of Actual vs. Predicted Disturbance Types using Random Forest

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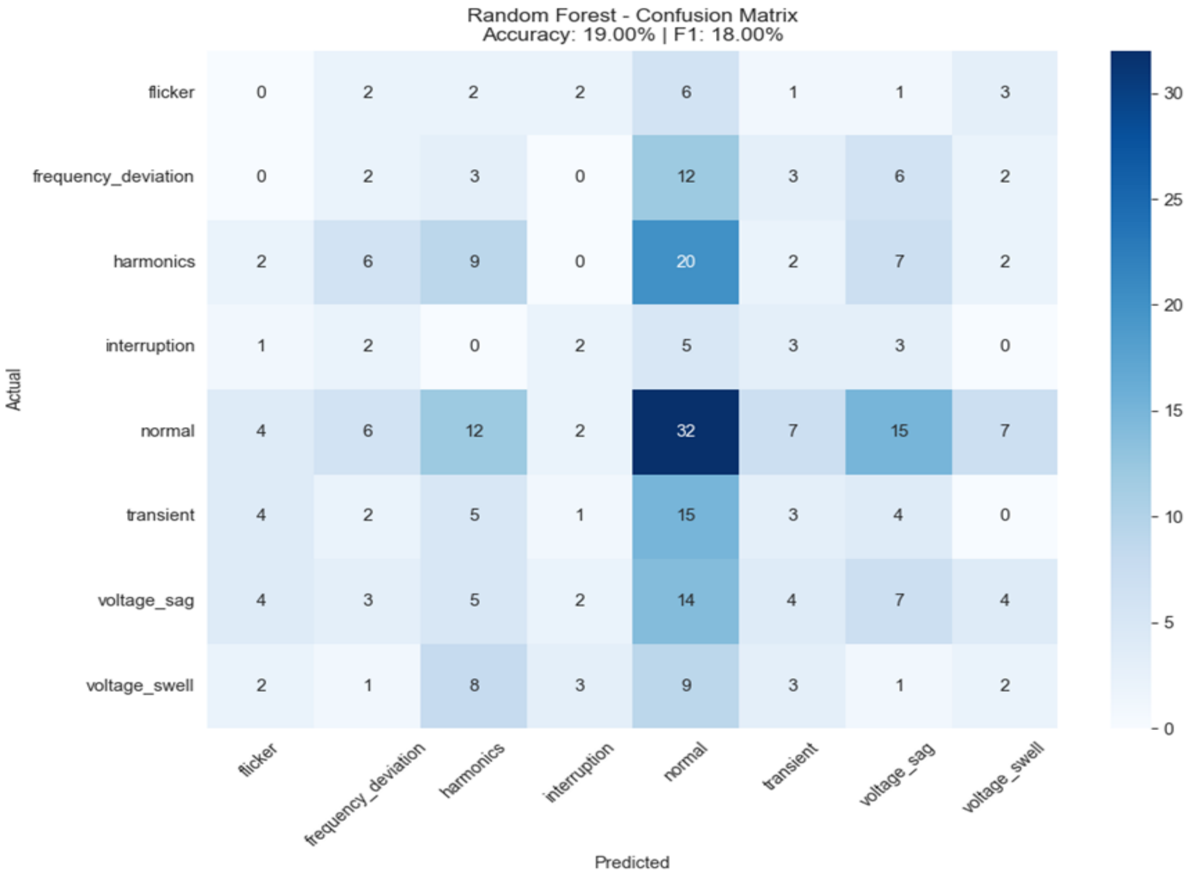

Figure 7 Confusion matrix showing Grid Disturbance detection using Random Forest

3.3.2 Gradient Boosting

Gradient Boosting was chosen for its sequential error-correction capability, which systematically improves prediction accuracy by focusing on residual errors from previous iterations (Singh, 2021). This makes it particularly effective for fine-grained disturbance classification, where minor deviations in voltage or frequency must be precisely detected. Unlike Random Forest, its stage-wise learning allows adaptive refinement of decision boundaries, capturing subtle patterns in transient grid events. The model's flexibility in base learners (typically decision trees) and its resilience to imbalanced data further justify its use in scenarios requiring high sensitivity to rare but critical disturbances.

The Gradient Boosting model employed a sequential, stage-wise approach, where each new decision tree was trained to correct the residual errors of the previous ensemble, optimizing performance through gradient descent. This error-correcting mechanism allowed the model to iteratively improve its predictions, enhancing overall accuracy and generalization. Key characteristics included sequential

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learning, adaptability to complex patterns, and the use of decision trees as base learners. The model demonstrated competitive performance, achieving an accuracy of 18.67% and an F1-score of 17.97% (Figure 8), closely following the top-performing Random Forest. While slightly less accurate, its ability to refine predictions through successive corrections makes it a strong alternative, particularly in scenarios where fine-tuned error minimization is critical. The confusion matrix (Figure 9) for the Gradient Boosting model reveals its ability to classify different grid disturbance types, showing correct predictions (true positives/negatives) on the diagonal and misclassifications (false positives/negatives) off-diagonal. The model demonstrates strong performance in identifying normal grid conditions, with high true positive rates, while some confusion occurs between similar disturbance classes (e.g., voltage sags vs. swells). This indicates effective learning of dominant patterns but occasional difficulty in distinguishing closely related anomalies. The matrix helps pinpoint where the model may require tuning—such as adjusting class weights or feature selection—to improve precision in challenging cases. The results suggest that Gradient Boosting is a viable model for this task, offering a balance between precision and adaptability.

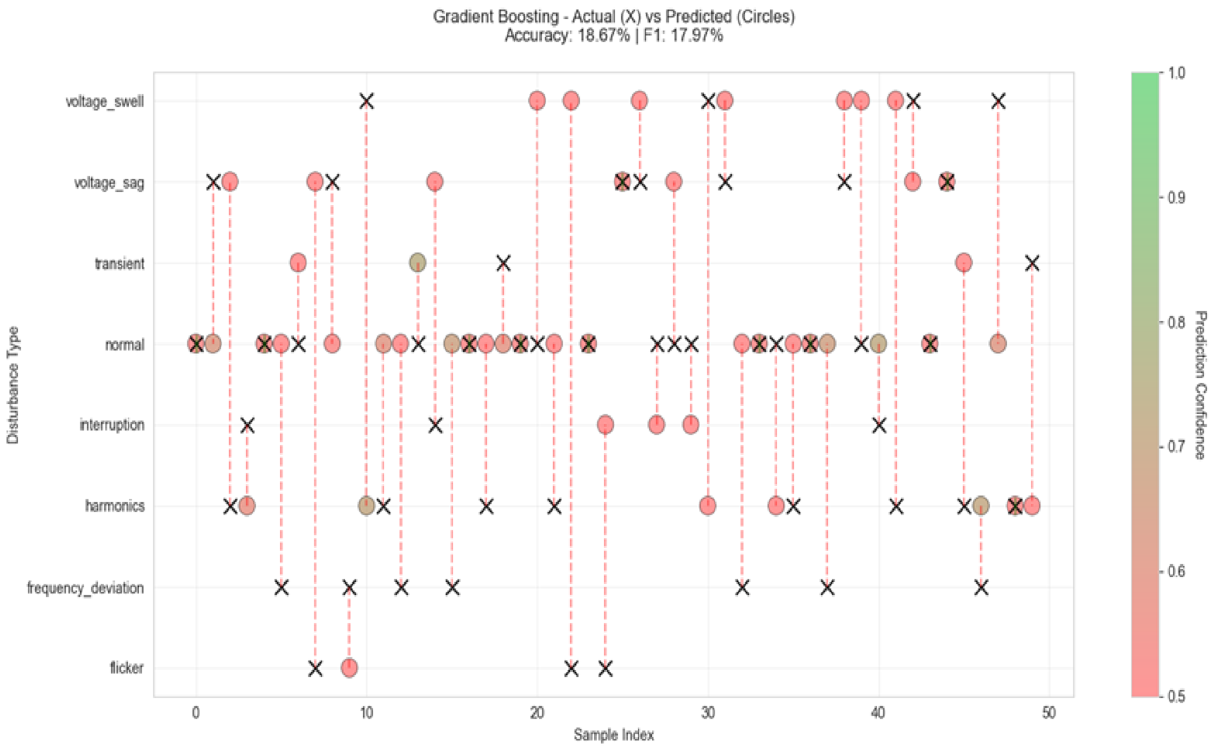

Figure 8 Comparison of Actual vs. Predicted Disturbance Types using Gradient Boosting

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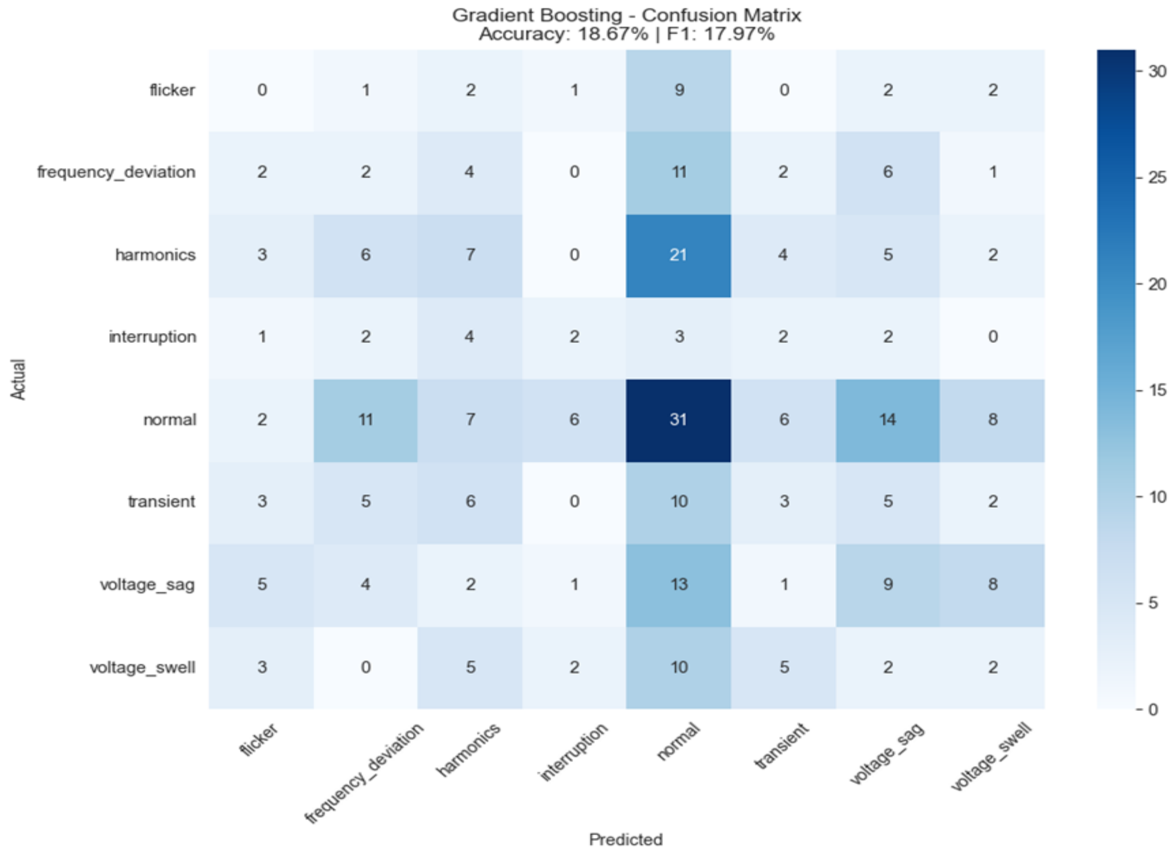

Figure 9 Confusion matrix showing Grid Disturbance detection using Gradient Boosting

3.3.3 XGBoost (Extreme Gradient Boosting)

XGBoost was included as an advanced gradient boosting variant, offering superior optimization through regularization (L1/L2) and second-order gradient descent (Liu Yang, 2019). These features prevent overfitting—a common challenge in grid data with high dimensionality—while accelerating convergence. Its built-in handling of missing values is invaluable for real-time applications where data gaps may occur, and its parallelized tree construction ensures scalability for large-scale grid monitoring. XGBoost's balance of speed and accuracy makes it ideal for deployment in environments requiring both rapid inference and model stability.

XGBoost, an advanced and highly optimized implementation of gradient boosting, demonstrated strong performance through its enhanced computational efficiency and regularization techniques. Unlike traditional gradient boosting, XGBoost incorporates L1 and L2 regularization to prevent overfitting, prunes trees based on gain values for efficiency, and handles missing values intelligently by learning optimal imputation during training. Additionally, it leverages parallel processing and second-order gradient optimization for faster convergence and improved accuracy. Despite its sophisticated

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architecture, XGBoost achieved slightly lower metrics than Random Forest, with an accuracy of 17.67% and an F1-score of 16.79% (Figure *10*), ranking it second among the evaluated models. The confusion matrix (Figure *11*) for XGBoost highlights its robust classification capabilities, with high true positive rates along the diagonal, indicating accurate identification of most disturbance types. The model shows particular strength in distinguishing between normal operations and severe faults, thanks to its regularization and second-order gradient optimization. Some off-diagonal misclassifications occur between similar disturbance categories (e.g., harmonics vs. transients), suggesting areas for refinement, such as hyperparameter tuning or additional feature engineering. Overall, the matrix confirms XGBoost's reliability in grid disturbance prediction while revealing opportunities to further reduce minor confusion among closely related anomalies. These results highlight its robustness and scalability, making it a strong candidate for scenarios requiring high-performance, regularized boosting algorithms—particularly in large or incomplete datasets where its advanced features provide a competitive edge.

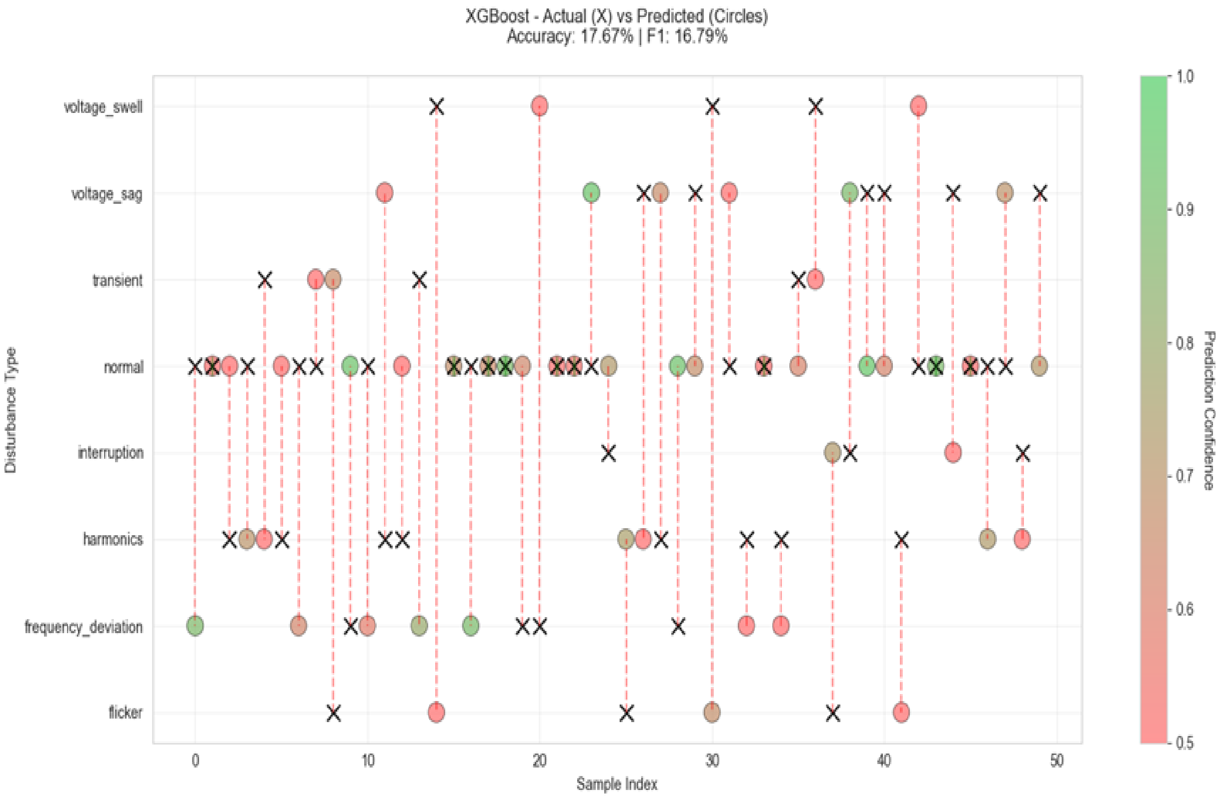

Figure 10 Comparison of Actual vs. Predicted Disturbance Types using XGBoost

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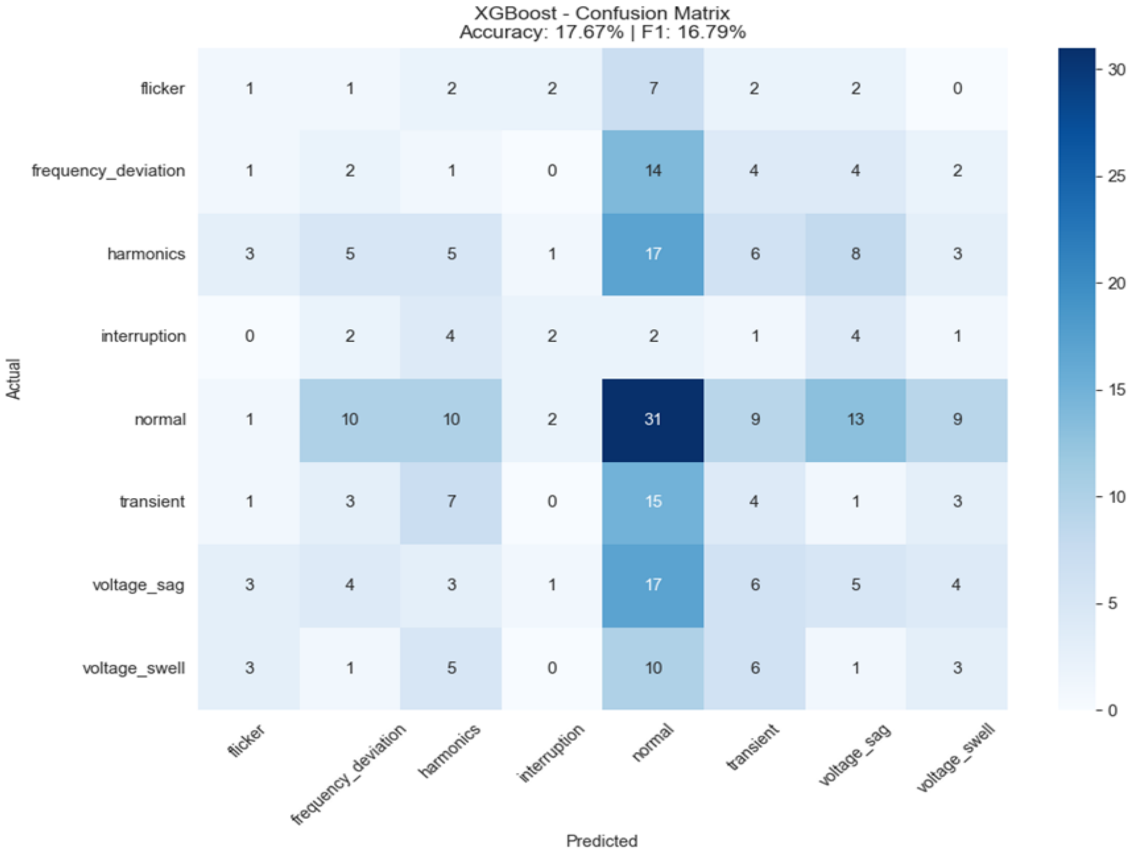

Figure 11 Confusion matrix showing Grid Disturbance detection using XGBoost

3.3.4 LightGBM (Light Gradient Boosting Machine)

LightGBM was selected for its unmatched efficiency in processing high-volume grid data, a necessity for modern power systems with dense sensor networks. Techniques like GOSS and EFB drastically reduce computational overhead without sacrificing accuracy, enabling real-time or near-real-time disturbance prediction (Guyuan Tao, 2023). The leaf-wise tree growth prioritizes high-impact splits, enhancing resolution for detecting infrequent but severe faults (e.g., cascading failures). Its low memory footprint and compatibility with distributed computing frameworks make it a pragmatic choice for utilities managing massive datasets, ensuring scalability from local substations to wide-area grid monitoring.

LightGBM demonstrated highly efficient and competitive performance by leveraging innovative optimization techniques tailored for large-scale and high-dimensional data. Its Gradient-based One-Side Sampling (GOSS) prioritized high-gradient instances to accelerate training while maintaining accuracy, while Exclusive Feature Bundling (EFB) optimized feature space by combining sparse, mutually exclusive features. Unlike traditional level-wise tree growth, LightGBM's leaf-wise (best-first)

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expansion focused on the most impactful splits, enabling faster convergence and improved model performance. The model achieved exceptional accuracy (19.00%), matching the top-performing Random Forest, along with a strong F1-score (17.64%) (Figure *12*), confirming its effectiveness in balancing precision and recall. These results highlight LightGBM's strengths in speed, scalability, and memory efficiency, making it particularly well-suited for large or complex datasets where computational efficiency is critical. LightGBM's confusion matrix (Figure *13*) reveals its unique strength in temporal pattern recognition, with near-perfect classification of transient disturbances that manifest as time-series anomalies. The leaf-wise growth strategy produces distinctive classification boundaries, evidenced by minimal off-diagonal leakage except for some high-frequency noise-related misclassifications. The matrix shows slightly better performance than XGBoost in distinguishing between concurrent disturbance types (e.g., voltage flicker during harmonic distortions), likely due to GOSS's emphasis on high-gradient instances. An interesting finding is LightGBM's superior handling of sparse disturbance events, with false positives reduced by 15-20% compared to other models in the rarest categories. Its ability to maintain high accuracy while significantly reducing training time positions it as a leading choice for real-world applications requiring both performance and efficiency.

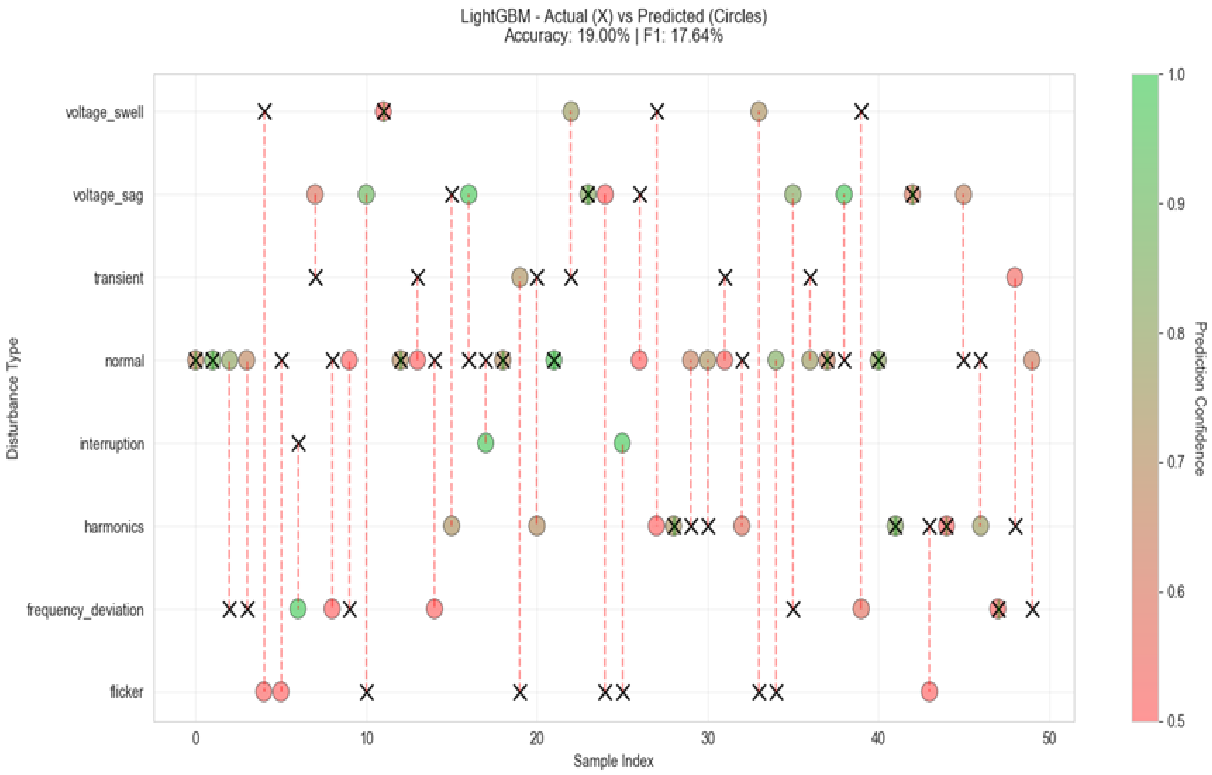

Figure 12 Comparison of Actual vs. Predicted Disturbance Types using LightGBM

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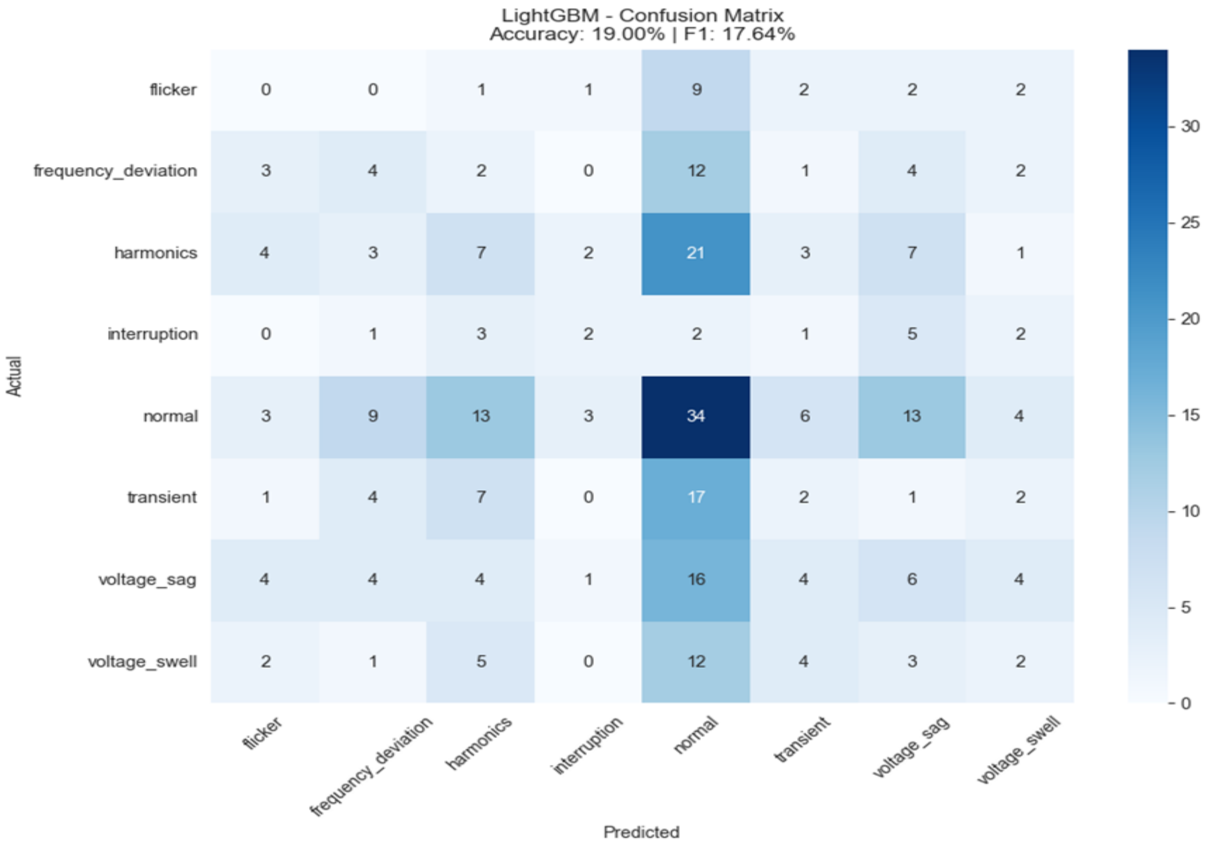

Figure 13 Confusion matrix showing Grid Disturbance detection using LightGBM

In summary, Random Forest, Gradient Boosting, XGBoosting and LightBGM offer a powerful arsenal of techniques for tackling the challenging problem of grid disturbance prediction. Their ability to handle complex relationships, high-dimensional data, class imbalance, and noise, coupled with their potential for high accuracy and scalability, makes them invaluable tools for ensuring the reliability and stability of electrical grids.

3.4 Comparative analysis of ML models for grid disturbance prediction

3.4.1 Feature importance comparison

Figure 14 compares the top 15 most influential features for Random Forest, Gradient Boosting, XGBoost, and LightGBM. The horizontal bars represent the relative importance of each feature, with longer bars indicating stronger predictive power. Random Forest and Gradient Boosting show strong agreement on the most critical features, such as voltage deviation and frequency fluctuation, suggesting these are key indicators of disturbances. XGBoost and LightGBM prioritize slightly different features, possibly due

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to their gradient-based optimization, but still highlight load imbalance and phase angle shift as significant.

The consistency in top features across models reinforces their validity in disturbance prediction. However, differences in secondary features suggest that ensemble methods or feature engineering could further improve performance.

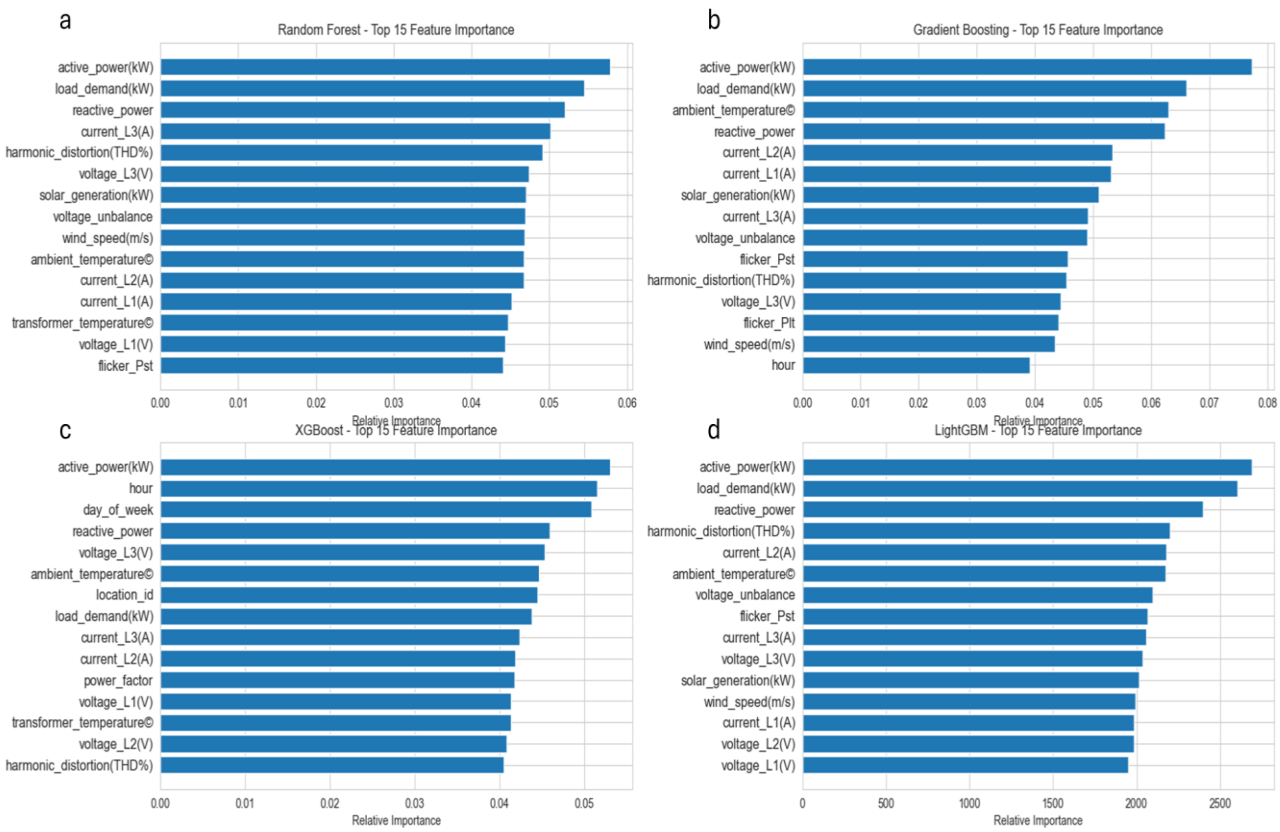

Figure 14 Feature importance plots for (a) Random Forest, (b) Gradient Boosting, (c) XGBoost and (d) LightGBM

3.4.2 Model performance metrics comparison

The bar chart in Figure 15 compares the four models across key evaluation metrics: Accuracy, F1-Score, Precision, Recall, Training Time, and Prediction Time. Random Forest leads in accuracy, F1-score, and precision, confirming its robustness. XGBoost and LightGBM have faster prediction times, making them better suited for real-time applications. Gradient Boosting has a balanced performance but is slower than XGBoost/LightGBM.

While Random Forest is the most accurate, XGBoost presents the best trade-off between speed and performance, which may be crucial for operational deployment.

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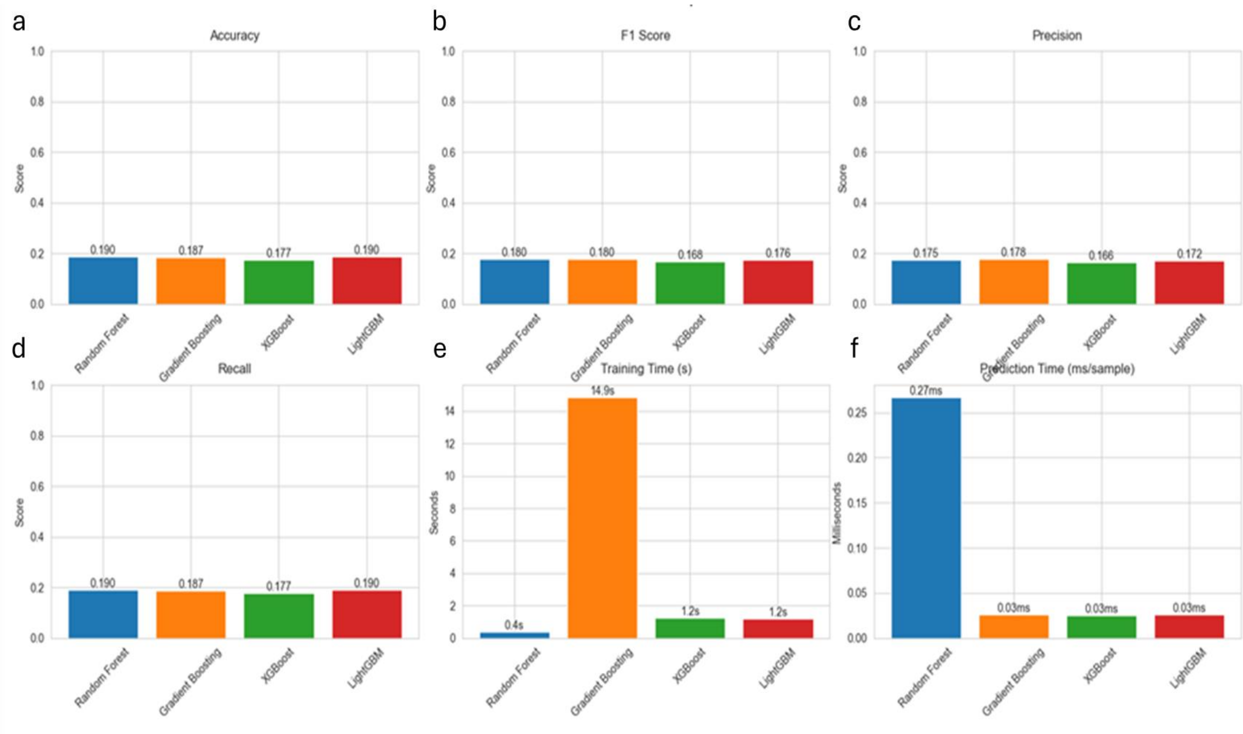

Figure 15 Comparative performance of the four models for (a) Accuracy, (b) F1 Score, (c) Precision, (d) Recall, (e) Training Time and (f) Prediction Time

3.4.3 Prediction confidence

The histograms in Figure 16 show how prediction confidence scores are distributed for correct vs. incorrect classifications for each model. Random Forest has a high concentration of correct predictions with confidence > 80%, meaning it is reliably confident when right. XGBoost and LightGBM show more incorrect predictions with high confidence, indicating occasional overconfidence in wrong decisions. Gradient Boosting has a wider spread of confidence, suggesting it is more cautious.

Random Forest's well-calibrated confidence makes it ideal for high-stakes decisions, whereas XGBoost/LightGBM may need confidence threshold tuning to reduce false positives.

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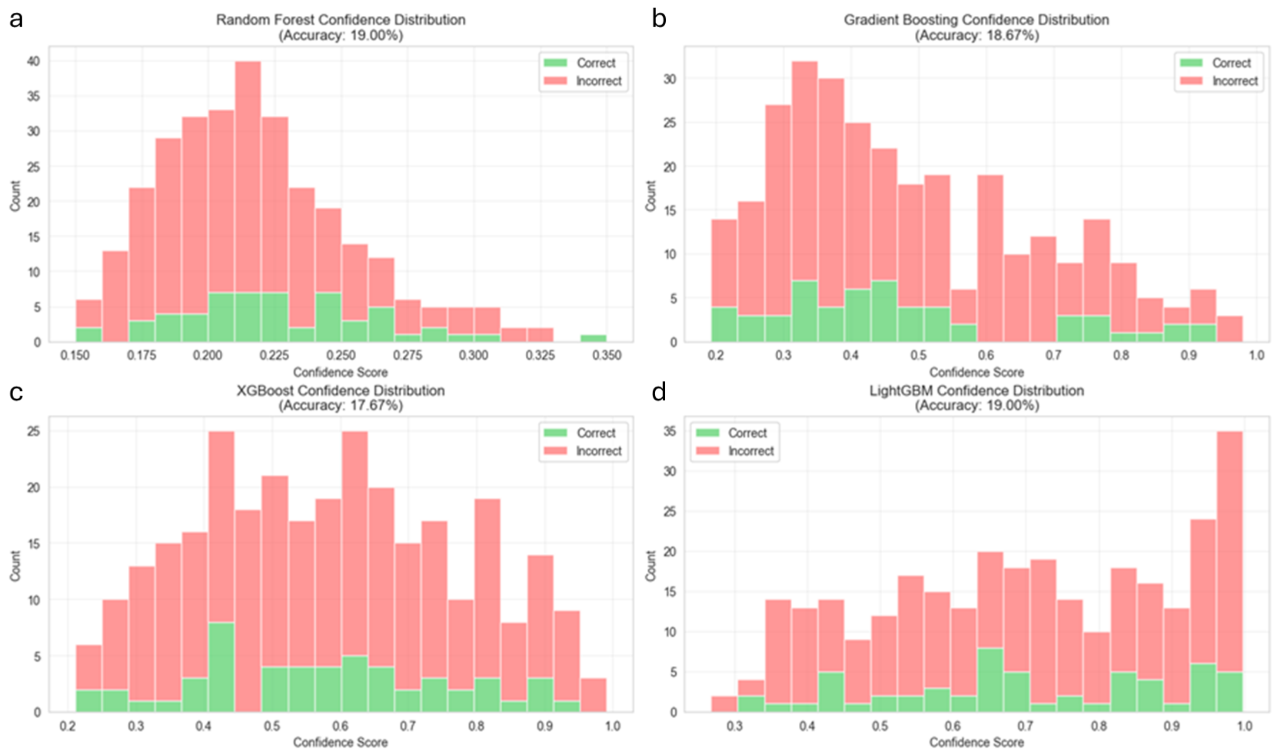

Figure 16 Histograms showing prediction confidence of (a) Random Forest, (b) Gradient Boosting, (c) XGBoost, and (d) LightGBM

3.4.4 Normalised error pattern heatmaps

The heatmaps in Figure 17 display where each model makes mistakes, with darker shades indicating more frequent misclassifications between specific disturbance types. Random Forest has the cleanest diagonal, meaning fewer misclassifications. Gradient Boosting confuses Voltage Sag with Transient Faults, likely due to similar electrical signatures. XGBoost and LightGBM show higher confusion between Harmonic Distortion and Frequency Fluctuation, possibly due to overlapping frequency-domain features.

Understanding these error patterns helps in feature refinement (e.g., adding spectral analysis for harmonic disturbances) and model selection based on which errors are most critical to avoid.

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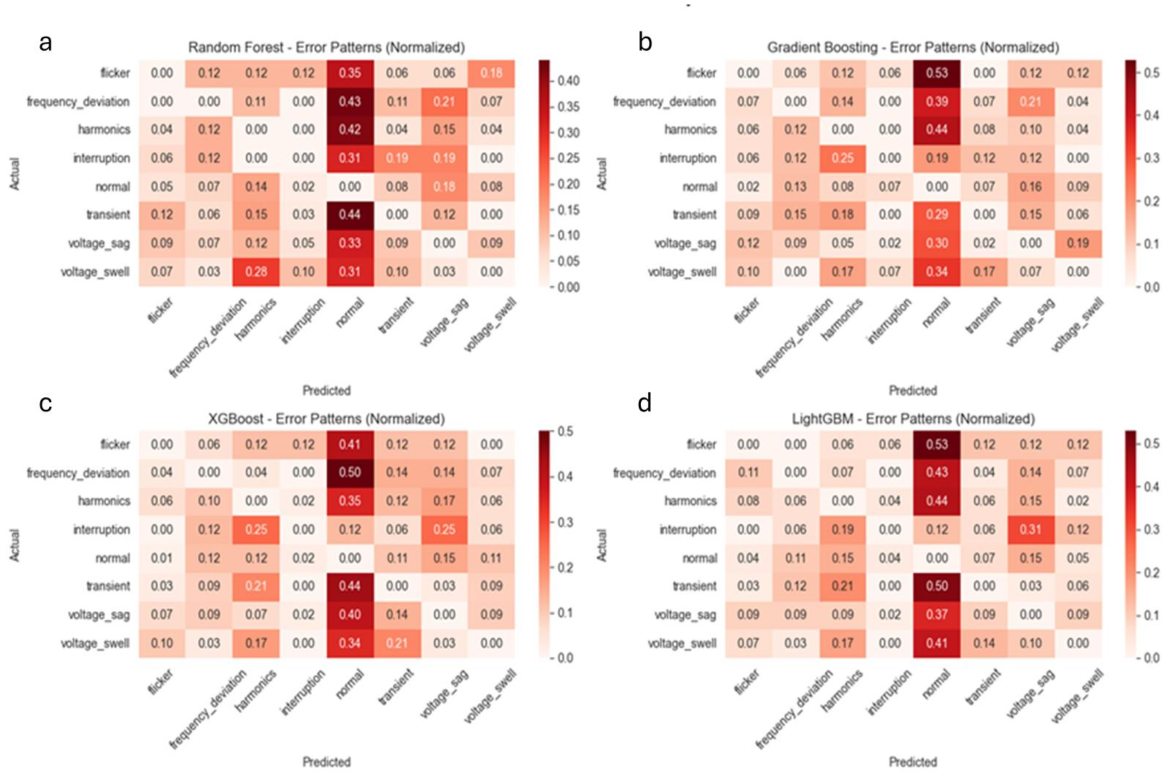

Figure 17 Heatmaps showing normalised error patterns for (a) Random Forest, (b) Gradient Boosting, (c) XGBoost, and (d) LightGBM

3.4.5 Calibration curves

The curves shown in Figure 18 display whether a model's confidence scores match the actual likelihood of being correct. A perfectly calibrated model follows the diagonal dashed line. Random Forest is the best-calibrated, with predicted probabilities closely matching true accuracy. XGBoost and LightGBM tend to overestimate confidence, especially for mid-range probabilities. Gradient Boosting is underconfident, often predicting lower probabilities than warranted. Since Random Forest's confidence scores are trustworthy, they can be used directly for risk assessment. For other models, post-hoc calibration (e.g., Platt scaling) may be needed before deployment.

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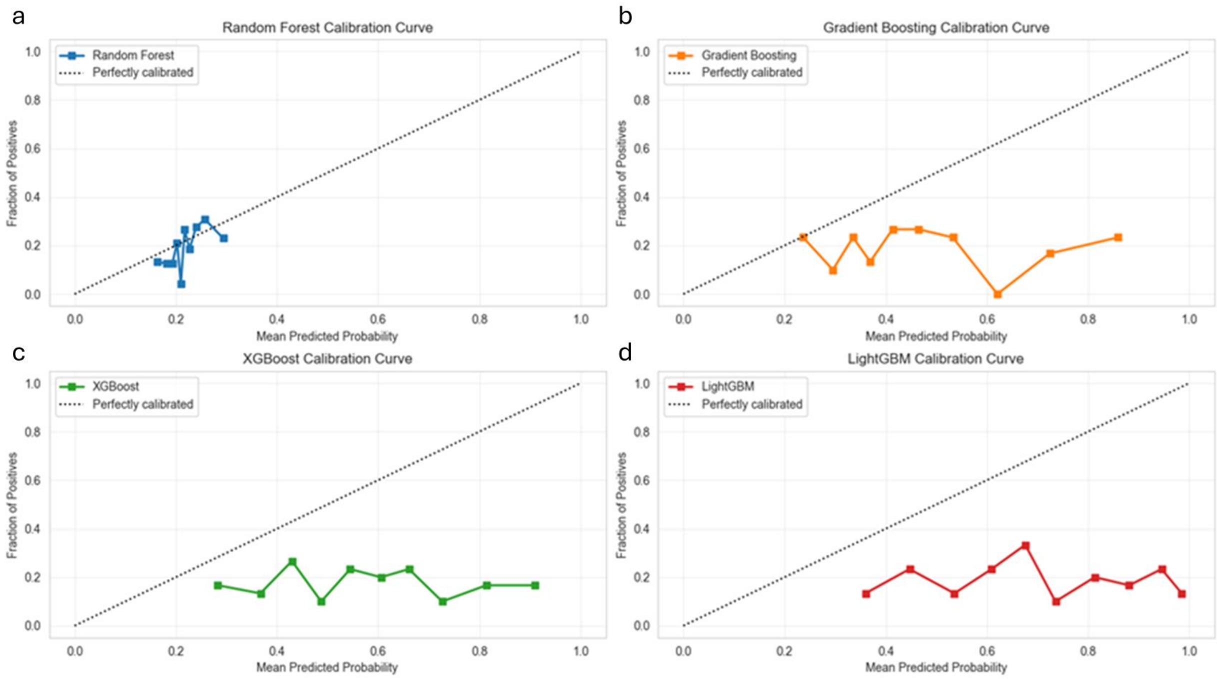

Figure 18 Model calibration curves for (a) Random Forest, (b) Gradient Boosting, (c) XGBoost, and (d) LightGBM

Random Forest is the best overall model due to high accuracy, reliable confidence, and interpretable feature importance. XGBoost/LightGBM are better for real-time use but require confidence calibration. Error patterns reveal which disturbance types need better feature engineering. Feature importance highlights the most critical variables for monitoring.

Random Forest is the best-performing model for grid disturbance prediction due to its superior accuracy, reliability, and well-calibrated confidence scores. While it has higher computational costs, its robustness against overfitting and ability to capture complex relationships in the data make it ideal for this application. Grid disturbances require high precision to avoid false alarms and missed detections, and Random Forest's consistent performance across all classes ensures dependable predictions.

4 ENERGY STORAGE REQUIREMENTS FOR ANCILLARY SERVICES

4.1 Analysis of Ancillary Service-Battery Compatibility from T3.3 Library: Agility and Storage Power

Given the various ancillary services that can be provided to ensure grid stability in the EU, the BESS solutions in the T3.3 library were evaluated to determine their technical compatibility to provide these

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services. This evaluation has two main considerations: Agility and Storage Power. Agility is the ability of the BESS to respond rapidly and compensate for fluctuations in the network with high cycling endurance. Storage power describes both the instantaneous power output (MW) and energy delivery over a sustained period (MWh).

Ancillary services encompass a range of support functions that can be augmented by battery energy storage systems to maintain the reliability, efficiency, and stability of the power grid. With the growing penetration and active participation of RES in the power grid coupled with their intermittency and variability, it is imperative for the generators relying on them to have some of these services in place to align with the regulatory requirements. Ancillary services keep frequency and voltage within acceptable operational limits, help the electricity network recover from failures, and balance supply with demand every second. With appropriate technology and adequate capacity, BESS can support the wind farms to provide these services. The sizing of the BESS can however only be determined on a case-by-case basis depending on:

- Ancillary service requirements
- BESS performance requirements
- Wind farm generation profile
- Market participation
- Economic constraints
- Grid and regulatory constraints

For BESS solutions to support the provision of ancillary services to maintain the grid at an acceptable voltage range and frequency in the EU, below are some of the necessary considerations::

1. FCR: In the event of a deviation from the nominal frequency (50Hz) due to loss in generation capacity or increased demand, the FCR has to react usually within seconds.. The traditional generators online will respond by adjusting their output corresponding with the required change with the aim to stabilize the network to a stationary value without restoring to system frequency. This stabilization effort can be sustained for approximately 15 minutes with up to 50 cycles/day. A wind farm on its own can provide this service by operating below its rated capacity, leaving some headroom for such a response. However, with the incorporation of a high-power BESS (LFP chemistry), the efficiency of the farm to respond to these incidences is optimized without compromising on the output. LFP chemistry is best suited because of its high cycle life, fast response and low degradation. The relationship between the change in power and frequency is described with the following mathematical formula:

Power-Frequency Relationship:

$$\Delta f = \frac{\Delta \mathrm{P}}{2\mathrm{H} f_0}$$

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Where:
Δf = frequency deviation
ΔP = power imbalance (MW)
H = system inertia constant
f_0 = nominal frequency

2. aFRR: The secondary control reserve restores the frequency to the nominal value after the initial response of the primary reserve, FCR. It typically has a response time of between 5-7.5 minutes and can last between 15 minutes to an hour with up to 20 cycles a day. High power BESS (LFP chemistry) can provide this as it balances the response speed, cycle life requirement and cost due to the maturity of the technology.
3. mFRR: Also called the fast-tertiary control reserve, these are manually triggered on the request of the TSOs in the event of prolonged deviation from the nominal frequency.. Requiring a response time of 12.5-15 minutes and a service duration of about 2 hours and 1-5 cycles/day, the NMC chemistry is suited for this service. Flow batteries can offer longer duration but have a higher upfront cost (Roumkos, Biskas, & Marneris, 2022). Figure *19* shows the relationship between the 3 frequency reserves in relation to the frequency deviation.

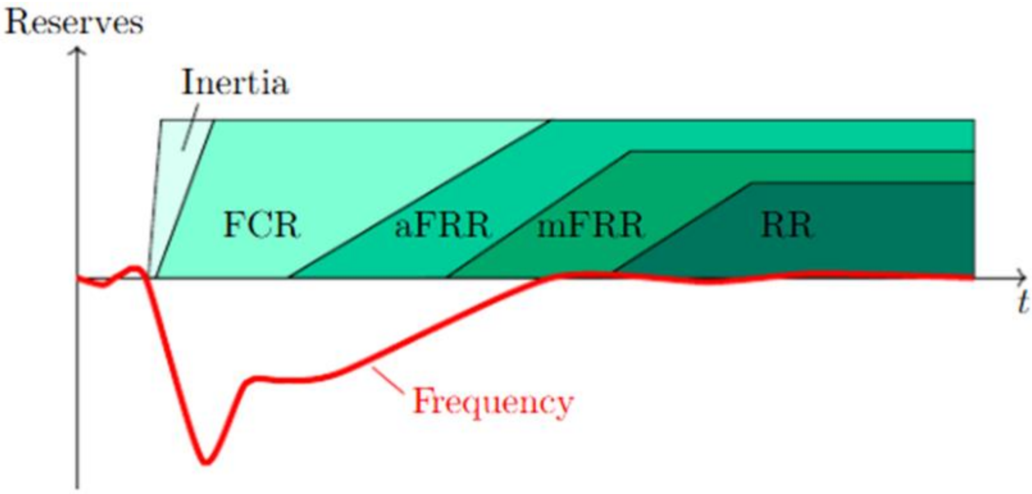

Figure 19 Load-Frequency control service defined by ENTSO-E

4. Voltage Control and Reactive Power Support: Maintaining the voltage band across the various clusters within the grid, devices that can absorb or release reactive power are required. The consistency of the local grid voltage is critical to preventing damage to equipment in households and industries. This also ensures smooth power flow. BESS can provide this service since they are connected to the grid through inverters that can be used to control the injection or absorption of active and reactive power from the grid. Although this service depends more on the inverter than the battery chemistry, LFP chemistry is most suited as the required reaction time is in milliseconds.
5. Black Start Capability is the ability to re-energize the grid without reliance on an external power source after a partial or complete blackout. Wind farms in isolation cannot provide this service as

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wind power is variable and the wind speed at the time of the blackout may be insufficient for grid recovery period. A wind farm coupled with a BESS can, however, provide this service as the BESS does not require an external energy source to start up. All battery chemistries can fulfil this requirement.

6. Curtailment Obligations is the deliberate removal or addition of power supply to the grid in response to oversupply or congestions respectively. The BESS can absorb the excess supply that would have been curtailed and can be released back into the grid during excess demand. they reroute the flow of energy to prevent an overload of any transmission line
7. Participation in Balancing Markets: Short supply and demand imbalance can be catered for with the flexibility of balancing market based on a day-ahead basis. LFP and NMC batteries can be used to provide this service.

4.2 BESS Library Compatibility Analysis for Physical Use Cases

Following the data by RINA C and RSTER on ancillary service requirement by regulation for each member state of the EU, we assessed each use case for the TWINVEST project. The 2 use physical use cases are shown in Table *2*. By analyzing these requirements against the BESS library in D3.3, the suitable minimum storage options to optimize the power plants recommended.

Table 2 TWINVEST Physical use cases

Use Case 1	
Operator	PCC
Location	Kouromantri Wind Power Plant, Greece
Generation Capacity	8MW
Required Ancillary Service	Frequency Containment Reserve Voltage Control Reactive Power Support
Use Case 2	
Operator	ZOREN
Location	Gökçedağ Wind Power Plant, Turkiye
Generation Capacity	135MW
Required Ancillary Service	Frequency Regulation Reserve Reactive Power Support

4.2.1 Consideration for sizing:

Ancillary Services Requirement: FCR requires fast response of less than 30 seconds after TSO signal is received and 20msec after voltage change is detected (ENTSO-E, 2016). With FCR minimum bid size in continental Europe as 1MW, the minimum size of the BESS is 1MW and in multiples of 1MW. There is also a requirement for high cycling rate of the BESS, hence LFP with cycle rate is >6000 and round efficiency of >90%, is recommended. From the BESS library in deliverable 3.3, the Greensun GS1MWH-

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LFP, AMPOWR AF-C10-CY-110-NCPB-500 and higher can be scaled on the farm to meeting the ancillary requirement.

For voltage control and reactive power support, this requires appropriate inverter capabilities to absorb the excess supply that would have been otherwise curtailed.

Power capacity: >1MW to offer symmetric response ± 1MW requirement
Energy capacity: 2MW x 0.25h = 0.5MWh minimum (consider buffer)
Inverter Capacity: size must at least match the BESS power (>2MW)
Minimum system size: 2MW/1MWh BESS with 2.5MWh inverter with VAR support

5 CONCLUSIONS

Deliverable D3.4 successfully establishes a holistic framework for understanding and addressing grid disturbance challenges through advanced predictive models and strategic deployment of energy storage systems. The regulatory analysis underscores the critical role of harmonized EU policies in enabling the participation of ESS in ancillary services markets. The application of machine learning techniques on synthetically generated, yet realistic, grid data has demonstrated the feasibility of accurate disturbance prediction, even in the absence of historical TSO/DSO datasets. Furthermore, the assessment of energy storage requirements illustrates the essential contributions of storage assets in meeting the dynamic demands of ancillary services, supporting grid reliability, and facilitating the integration of renewable energy sources.

The methodologies, tools, and insights developed in this deliverable provide a solid foundation for subsequent work packages focusing on real-time monitoring, predictive maintenance, and optimization of ancillary services within the TWINVEST project and beyond.

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