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Towards low-inertia power systems: An overview of monitoring technology, challenges and emerging solutions

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ABSTRACT

The interaction of hybrid energy generation resources and the nature of electrical heterogeneous demand on power systems are reshaping power system operation and its dynamic behavior. The high penetration of inverter-based resources (IBRs) is defining the features of grid operation. Low-inertia power systems (LIPS) experience faster transients and weaker system strength, making them more vulnerable to large disturbances. In this document, the IEEE Working Group (WG) on Big Data & Analytics for Transmission Systems combines their knowledge and collective efforts to provide a comprehensive, multidimensional understanding of the current challenges in LIPS. First, the system-level services based on ancillary services and the relevance of wide-area measurement system (WAMS), interoperable control and visualization platforms, as well as the structures of different IBRs are discussed. Then, the current challenges in distribution and transmission systems, as well as potential solutions related to synthetic inertia to reduce the Rate of Change of Frequency (ROCOF), the use of dynamic voltage regulators to support transient events, and WAMS technology used to control and operate on different timescales of dynamic phenomena are addressed. Finally, a future outlook is provided were the main conclusion of the WG is that harmonizing high-speed monitoring standards and developing robust, data-driven methods based on artificial intelligence (AI) and machine learning (ML) for the coordinated operation of mixed fleets of grid-following and grid-forming, as well as the integration of human operators into increasingly automated control environments, are promising avenues for achieving resilient and flexible power systems.

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1. Introduction

This work represents a collective effort of the international and multidisciplinary IEEE working group (WG) on big data and analytics on transmission systems. The experience of the members spans across multiple disciplines such as power systems dynamics and control, power electronics, instrumentation and measurements, and analytic methods for power systems. The mission of the group is to demonstrate how data analytics can be used to develop solutions to the problems currently faced in power systems and to facilitate decision-making in the control room of transmission system operators (TSOs). The group was established in 2020 as Task Force (TF) and elevated to WG in 2023. The activities of the group include regular online and in-presence meetings, organization of panel and tutorial sessions in major IEEE conferences, publications and organization of special issues in high impact journals, international workshops and technical reports. The group's activities have been recognized by the IEEE with awards such as the Outstanding Working Group Award in 2024. Drawing on the combined knowledge of the authors, the document integrates perspectives that would be difficult to obtain without the joint efforts of the working group. This document incorporates varied insights, analyses, and practical considerations of professional and academic experts. The aim of this paper is to provide a comprehensive and multidimensional understanding of the current challenges in low inertia power systems (LIPS) and also give the author' s opinion of the future outlook.

To introduce the problem discussed in this document, it is important to first introduce the current situation and evolution of the electrical grids and that ensuring the safe operation of this critical infrastructure is a cornerstone of modern civilization. Virtually every aspect of social and economic life—ranging from healthcare, transportation, and communication to manufacturing and digital infrastructure—depends on a continuous and stable supply of electricity. However, recent events in major power systems around the world have demonstrated that large-scale events can occur suddenly and have devastating consequences. These events can disrupt essential services, cause significant financial losses, threaten public safety, and erode confidence in the resilience of national infrastructure.

At the same time, electric power systems are undergoing a profound transformation. The rapid integration of renewable energy sources (RES) and distributed energy resources (DER), coupled with the growing electrification of transportation and heating, is making grid operation increasingly complex and dynamic. While these changes are crucial for achieving sustainability and decarbonization goals, they also introduce new vulnerabilities and operational challenges. Intermittent generation, reduced system inertia, and the proliferation of decentralized components increase the risk of instability and cascading failures if not properly managed.

Moreover, the nature of electrical demand is shifting significantly as well. The rapid digitalization of society is driving substantial growth in electricity consumption, particularly influenced by the emergence of large data centers [1–3] that require significant amounts of energy to support cloud services, artificial intelligence workloads, and global connectivity. Additionally, the widespread adoption of electric vehicles, the deployment of distributed storage systems, and the expansion of smart digital tools are all reshaping load profiles and adding new layers of complexity to power system operation. These changes are redefining both the supply and demand sides of modern grids, underscoring the need for flexible, resilient, and intelligent electrical infrastructure.

1.1. Low inertia power systems

The concepts of conventional and fully renewable power systems are graphically depicted in Fig. 1. The main difference is the replacement of traditional synchronous generators with power electronic components or inverter-based resources (IBRs), resulting in low-inertia power systems (LIPS). Renewable sources continue growing slowly around the world and the global capacity is expected to double by 2030 [4]. Solar PV is dominating the global growth of RES, accounting for almost 80 %

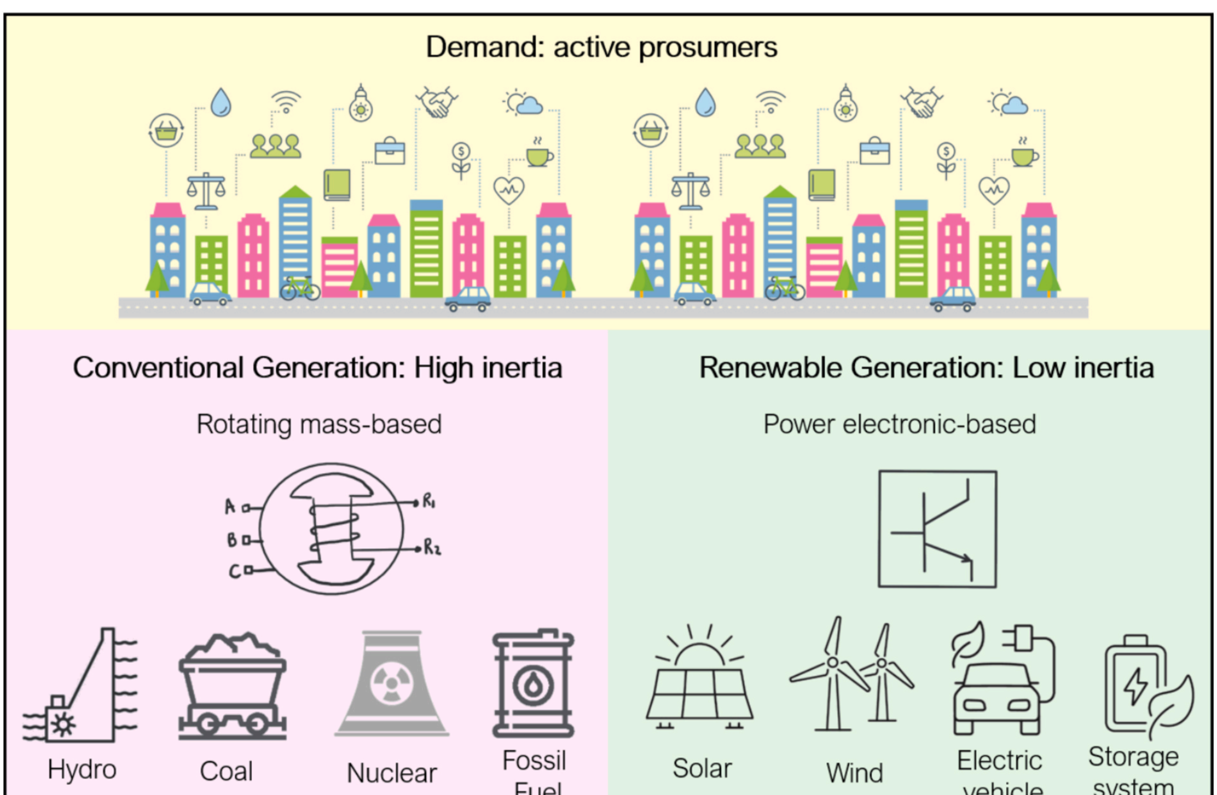

Fig. 1. Difference between a high-inertia and a low-inertia power system.

of the global increase, followed by wind, and other sources of RES such as hydropower, bioenergy and geothermal, which are not necessary IBRs. Today, power grids around the world are no longer dominated by conventional generation and cannot be represented entirely as in the left-hand side of Fig. 1. However, they are not still completely renewable as in the right-hand side of Fig. 1, but are clearly moving towards this direction. One of the main concerns in LIPS is the heightened risk of frequency instability. The reduced rotational inertia limits the system's ability to maintain frequency and the rate of change of frequency during sudden supply–demand imbalances, making it more susceptible to disturbances, which can cause significant frequency deviations.

In April 2025, the electrical infrastructure of continental Europe experienced a blackout in Portugal and Spain, affected also a small area in Southwest France. Fig. 2 display the frequency collapse in Spain from synchrophasor data collected in Switzerland where the local frequency is displayed along with the frequencies excursions of Lativa (LV) and Malaga (ES). In this figure, it can be clearly seen that the system collapsed at 12:33 pm. For about ten hours, more than 50 million people were affected without access to basic services such as health, transportation, and communication. Just before the blackout, Spain was operating with 71 % of its generation based on solar and wind energy [5]. Although the source of problem was not directly linked to the low levels of inertia in Spain, the network configuration during this day played a crucial role. The Iberian blackout has demonstrated that the trend of modern electrical networks is to become low inertia power systems (LIPS).

1.2. Taxonomy of Low-Inertia power systems

To address the issues resulting from LIPS, recent research has focused on two main areas: enhancing frequency response and developing advanced control strategies for inverter-based resources (IBRs). Techniques like synthetic inertia, also called virtual inertia, and fast frequency reserve/response has shown potential in improving frequency control and boosting the frequency response. Providing synthetic inertia effectively increases the inertia through inverter-based resources, with power electronic converters mimicking the behaviour of synchronous generators, while fast frequency reserve helps mitigate frequency deviations. This document presents a classification of security and stability phenomena in low-inertia power systems. The grouping organizes and categorizes these phenomena systematically, facilitating analysis and the identification of common properties among the classified items. It focuses on their origins and potential research and development approaches for effective mitigation, including the use of big data techniques.

The classification of power system stability in conventional and low-inertia power systems is illustrated in Fig. 3. In this figure, the classical stability problems that conventional power systems face are displayed, namely voltage, frequency and rotor angle stability constraints. In addition, the new stability phenomena that LIPs face such as resonance and converter driven stability (CDS) are also displayed. It is worth mentioning that CDS is a generic term that encompasses all stability phenomena influenced or caused by converters and their controls. These interactions can occur over different time scales and can be classified as slow (smaller than 10 kHz) or fast (larger than 10 kHz). While power electronic components (PECs) enable renewable energy integration and enhance grid flexibility, they are introducing new stability challenges including oscillations and dynamic interactions. Beyond the concerns of the classical stability constraints, the interactions among PECs arise the following concerns: the interactions involving PECs in parallel or too close to each other, the interaction between the passive components of the PECs with its own controls or with nearby controllers and the mutual interaction between the control loops of the PECs.

Low-inertia has become a major concern in modern electric grids due to the integration of RESs that have limited or no rotational inertia. This lack of inertia can lead to various security and stability issues that must be addressed to ensure the grid's reliable operation. LIPS exhibit reduced transient stability margins, making them more vulnerable to large disturbances such as faults or sudden changes in generation or load. Research and development efforts have focused on improving transient stability by developing advanced control schemes and coordination strategies. The integration of big data analytics can provide valuable insights into the system behaviour during transient events, aiding in the development and design of efficient and adaptive control algorithms.

1.3. Contribution and structure of the manuscript

The power sector has entered the era of digitalization, and sophisticated metering infrastructure is now in place, not as prototypes, but as standardized assets that are part of the new regulations to operate electrical grids. These high-resolution sensors with dedicated communication networks provide the operators of the system with more data than ever before. However, despite the amount of information collected on the network, the data alone is meaningless without analysis and only accumulates on servers. For this information to be meaningful and useful to address the new stability challenges, it must be processed using different data analytic tools, filters, and feature extraction methods.

This document is not a breakthrough research document but a review paper. Its main contribution is the varied insights, analyses, and practical considerations of professional and academic experts from the working group and its aim is to provide a multidimensional understanding of the current challenges in low inertia power systems.

The rest of the document is structured as follows: Section 2 provides

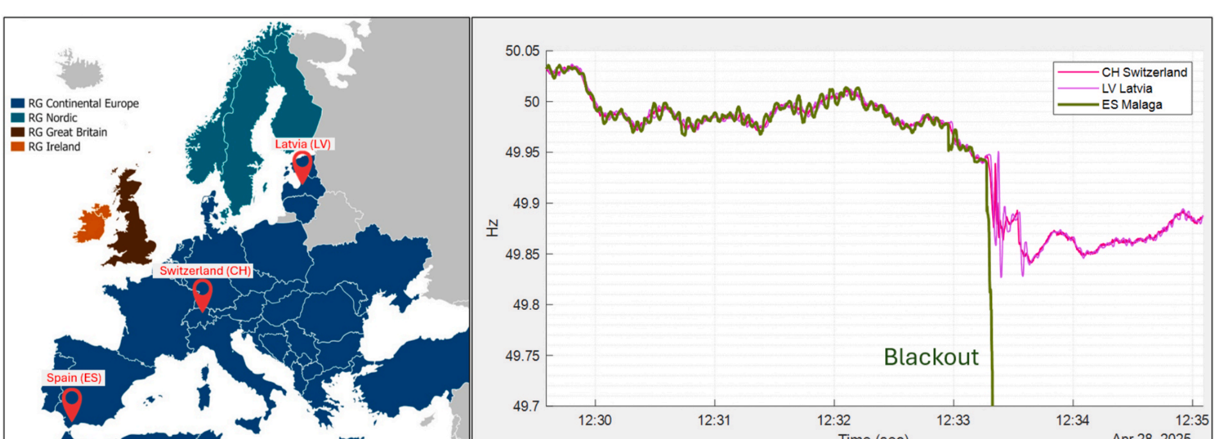

Fig. 2. Synchrophasor measurements in Switzerland, Latvia and Spain during the Iberian blackout, April 2025.

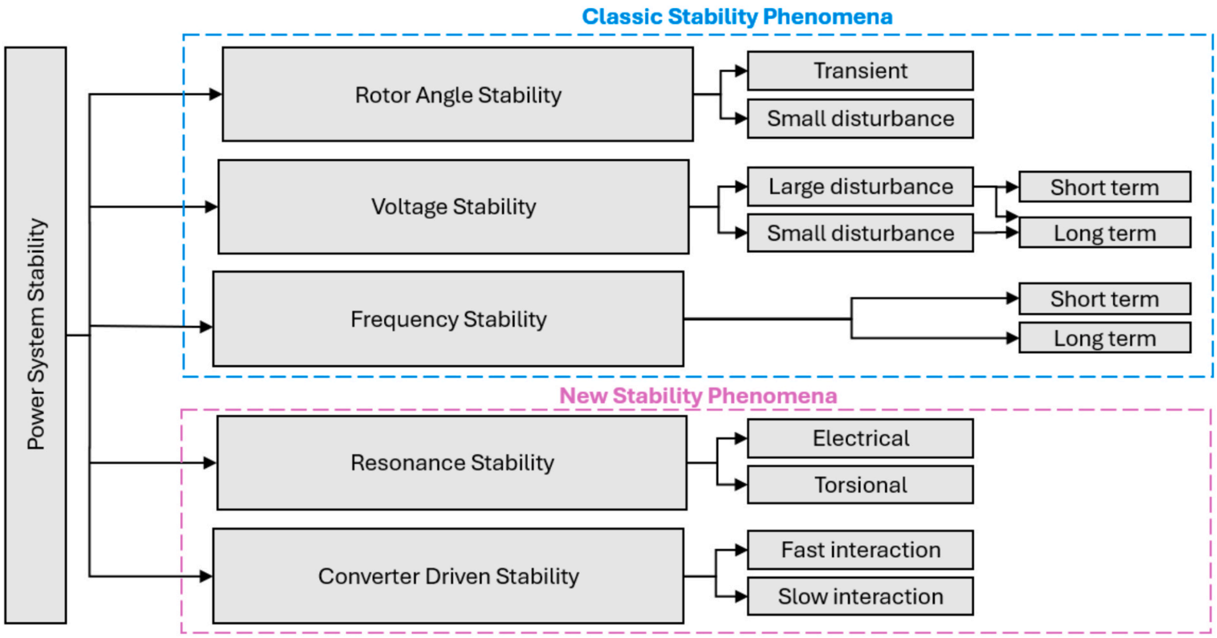

Fig. 3. Taxonomy of low-inertia power systems [6].

a comprehensive and detailed review of stability classification in LIPS. The following categories are therefore linked with the timeframes of dynamic and transient power system phenomena, as well as the modern smart grid infrastructure that can contribute to the stability of low-inertia systems: frequency stability, voltage stability, rotor angle stability, converter-driven stability and resonance stability. Section 3 discusses the operating requirements for low-inertia power systems. Due to new challenging operating conditions, transmission and distribution system operators must establish new, closer collaborations to guarantee stability and service quality. In this regard, many actions are envisaged, encompassing different sectors, from digital transformation strategies and grid reinforcement to policymaking and consumer engagement. Ancillary services are essential for maintaining frequency, voltage and system security in real time. They ensure stable operation during normal conditions and manage disturbances more quickly. Section 4 provides a detailed technical discussion of the enabling technology for rapid data acquisition and information extraction. This section presents the Hierarchical Wide Area System Monitoring System, which comprises a three-tiered structure that demonstrates how different devices collect data in real time from points of the grid and transmit it to the Central Control Centre for comprehensive grid analysis and management. It also discusses the performance comparison of different monitoring devices. Using the taxonomy of stability phenomena in LIPS, the applications of monitoring devices are classified to detect potential instabilities in different subcategories. Section 5 discusses the challenges of control and assessment in LIPS. It reviews and discusses the main operational challenges, including detailed simulations of EMT, grid reinforcement, ancillary services, real-time monitoring and so on, as well as the common challenges of distribution and transmission systems, such as line congestion, communication infrastructure, standardization and large-scale modelling. Section 6 closes the proposal by discussing potential solutions to the challenges faced by LIPS. New control protocols capable of dealing with faster and stronger disturbances are enlisted to overcome these challenges. Battery storage or demand response control could inject or absorb energy during transient events. Additionally, designing control inverters' power electronic circuitry to emulate "synthetic inertia" could reduce ROCOF variation. Dynamic voltage regulator and static VAR compensator controls must be tuned to help maintain voltage levels during load abrupt changes and disturbances. This section close with the aim of making the WAMS infrastructure the cornerstone for tuning multiple controls at these different time scales due to collected data could help to improve the power system modelling, developed new monitoring visualization of the system and provide a new framework to predict and control the LIPS based on AI and data analytic strategies.

2. Stability classification in Low-Inertia power systems

Before classifying the stability of a system, it is important to distinguish between the following concepts: security, stability, reliability and resilience. Security is the ability of the system to withstand disturbances such as line outages, generator trips or load changes, and continuing operating within acceptable limits. The security of the system includes contingency analysis (N-1, N-2, etc), as well as preventing and correcting actions. Moreover, power system stability is the ability of the system to return to a steady operating condition after a disturbance. Fig. 3 depicts the classic and new stability classification in power systems. Reliability, on the other hand, is the ability of the system to supply electricity continuously with acceptable quality. The concept of reliability encompasses two components: adequacy, which refers to having sufficient generation, and transmission resources under fault-free conditions and security, as defined before. Finally, resilience is the ability of the system to prepare, adapt and recover to high-impact and low-probability events such as extreme weather conditions, cyberattacks, or major equipment failures, which includes how rapid the system can recover [7].

Fig. 4 depicts the time scales for dynamic and transient phenomena, as well as the corresponding monitoring and control approaches. By investigating and addressing these phenomena, power system operators and researchers can ensure the reliable and secure operation of LIPS, facilitating the integration of RESs and the transition to a sustainable and resilient electric grid. Stability phenomena in low-inertia power systems can be broadly classified into the following categories: frequency stability, voltage stability, rotor angle stability, converter-driven stability and resonance stability. Stability phenomena in low- inertia power systems can be broadly classified into the following categories:

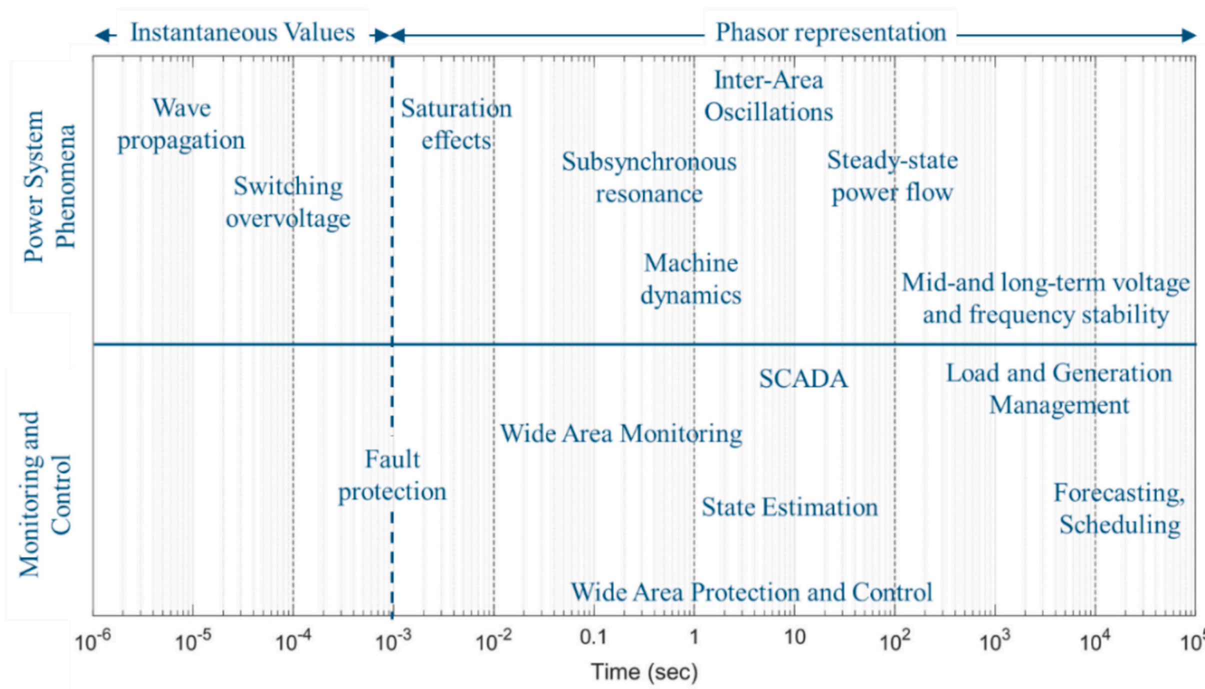

Fig. 4. Timeframes of dynamic and transient power system phenomena [8].

Frequency Stability: In LIPS, frequency stability becomes a critical issue due to the reduced rotational masses in the power system, i.e., inertia and the increased penetration of RESs. The sudden injection or withdrawal of power can result in rapid frequency changes and deviations. These deviations can trigger protective relays, leading to system-wide disruptions. To mitigate this, new control strategies and technologies are being developed to provide fast response and accurate frequency regulation.

Voltage Stability: LIPS can experience voltage stability issues due to the limited rotational masses available for transient voltage support. The intermittent nature of renewable generation can further exacerbate this problem. Voltage instability can lead to voltage collapse and voltage sags, which can disrupt the operation of sensitive loads. Advanced voltage control mechanisms and coordination between distributed energy resources and traditional voltage regulation devices are crucial to maintain voltage stability.

Rotor Angle Stability: Rotor angle stability can be subdivided into small-signal and transient stability. This stability refers to the ability of the power system to maintain synchronism following a disturbance, such as a fault or sudden changes in generation or load. In LIPS, the absence of large rotating masses may cause a higher susceptibility to transient stability issues. The response time to control actions needs to be significantly faster to prevent system-wide instability. Advanced protection schemes, fault ride-through capabilities, and enhanced control algorithms are essential to enhance transient stability in LIPS.

Converter-Driven Stability: IBRs in power systems rely on fast-response control loops like Phase-Locked Loops (PLL) and inner-current control loops, which exhibit cross-couplings with both electromechanical machine dynamics and electromagnetic transients of the network. The coupling effects may lead to unstable power system oscillations over a broad frequency range. These oscillations can arise from interactions between conventional synchronous generators and converter-interfaced RESs. The ability of PLLs to synchronize with the grid during faults is not always given. This causes inaccurate angle measurements and thus potentially leads to instability. Advanced oscillation detection, damping techniques and coordinated control of RESs are required to maintain safe operation of the power system. In addition, the tuning of PLL and inner-current control loops or enhancing system strength is advised. The interaction of passive power system components with fast inner-current loops of IBRs can cause high-frequency effects, such as switching resonances and mutual interactions between grid-connected converters. These can result in harmonic instability effects, multi-resonance peaks, high-frequency oscillations or super-synchronous stability problems in the presence of synthetic inertia controllers. Low-frequency oscillations resulting from the controller interaction of converters and other system components are often reported in weak grids with low short circuit ratios.

Resonance Stability: Resonance occurs when energy exchange happens periodically in an oscillatory manner, leading to the magnification of voltage/current/torque magnitudes. Resonance instability is characterized by the exceeding of specified thresholds in these magnitudes. In an alternating current system, various oscillating circuits can arise from different network components: between installed coils and capacitors (resonant circuits), between the rotating masses of generators and the electric grid and between system controllers of power converters. The phenomenon can result in large current and voltage oscillations, potentially causing damage to electrical equipment and mechanical components. Thus, any resonances that occur should be damped as well as possible. With the increase in converter-based systems, the possibilities for such interactions are increasing. As countermeasures, for example, power electronic components can be used that have a damping effect. Higher short-circuit power also has a positive effect on the resonance stability. Furthermore, control mechanisms can be implemented to avoid destabilizing interactions between controllers.

Investigating these security and stability phenomena requires a comprehensive approach involving both hardware and software solutions. Enhancements in grid infrastructure, such as advanced power electronics, energy storage systems, and smart grid technologies, can

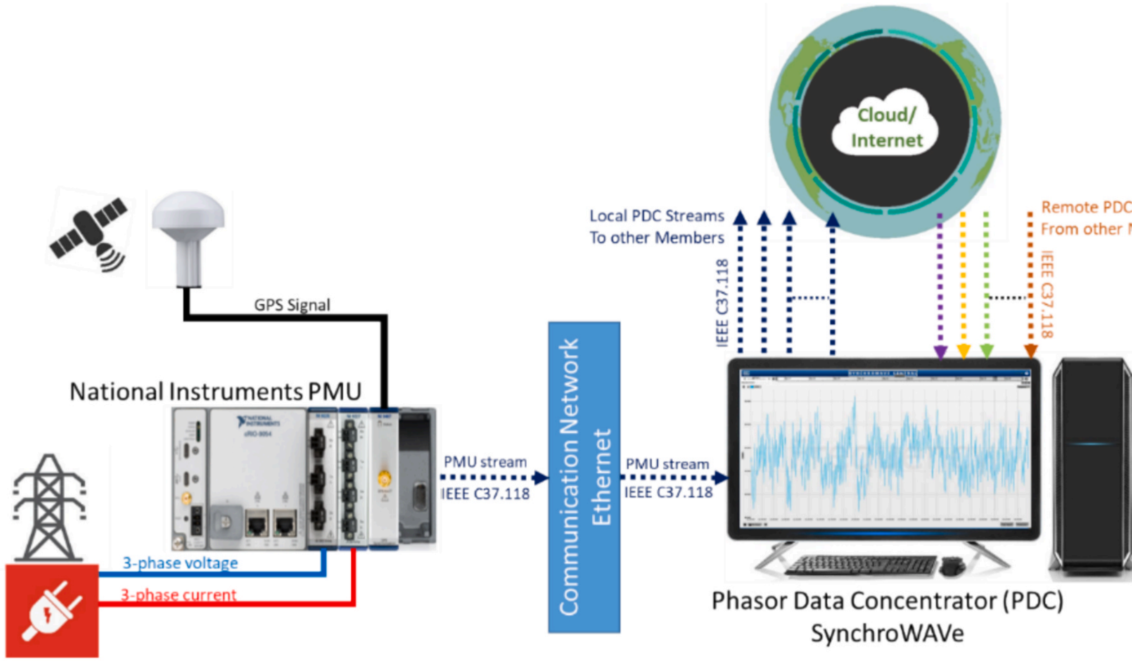

Fig. 5. Standard setup of a phasor measurement unit (PMU).

contribute to the stability of low-inertia systems. The proliferation of synchrophasor technology or phasor measurement units (PMUs) and the availability of extensive measurements from wide-area monitoring systems (WAMS) offer opportunities for the analysis and control of LIPS. These systems provide high-resolution, time-synchronized measurements across the grid, enabling real-time situational awareness and facilitating the detection and diagnosis of security and stability issues. The standard setup of PMU devices is depicted in Fig. 5. A comprehensive description of PMUs architecture and communication challenges can be found in Section 4. Applying techniques from machine learning and other fields such as signal processing and statistics, algorithms can extract valuable information from PMU measurements, supporting decision-making processes and enhancing system security. For example, some approaches can play a significant role in predicting and preventing voltage instability events by leveraging vast amounts of real-time measurements and historical data. Machine learning algorithms, combined with advanced data analytics, can provide accurate predictions of voltage stability margins and enable the implementation of preventive control actions.

3. Requirements to operate Low-Inertia power systems

One important question when operating a power system is: How reliable are you? The answer to this question is directly related to the economic capacity of the system operator in question. In other words, the more financial resources, the greater the amount of protection equipment and redundancy and hence, higher security.

The rapid integration of new paradigms for energy generation and storage represents one of the most important challenges for power systems, traditionally conceived as a centralized, complex and highly ramified network, from different points of view. The 2016 South Australia blackout and the 2025 Iberian blackouts serve as a representative examples of the operational challenges associated with low-inertia power systems [9]. For the case of the 2016 blackout in South Australia, at the time of the event, wind and solar generation accounted for over 40 % of the installed capacity in South Australia, with wind power contributing a significant share of real-time generation. The high penetration of non-synchronous renewable energy reduced the overall system inertia. When severe storms caused multiple network faults, the resulting voltage disturbances led to the disconnection of several wind farms due to their low- voltage ride-through settings. The subsequent rapid frequency decline could not be arrested due to the lack of synchronous inertia and limited primary frequency response, ultimately resulting in a state-wide blackout. This incident highlights the increased vulnerability of low-inertia systems.

The European Network of Transmission System Operators for Electricity (ENTSO-E) outlines the needs and motivations underlying such big changes [8]. On the one hand, the seamless integration of RESs is acknowledged as a global challenge and many government and control agencies have put in place severe policies to achieve significant reduction of the carbon footprint in the upcoming years. On the other hand, such a transition calls for a redefinition of the power system monitoring and control strategies. Indeed, RESs are typically dependent on natural phenomena related to weather conditions that are hard to control or even forecast with sufficient accuracy. Therefore, their power output might be sporadic, volatile and not correlated with the actual power demand. In this scenario, only a distributed and synchronized measurement infrastructure can provide a snapshot of the system's current state and possible evolution. Transmission and Distribution System Operators are required to establish new and closer collaborations to guarantee the stability and the quality of the service. In this regard, many actions are envisioned, encompassing different sectors, from digital transformation strategies, grid reinforcement, to policy making or consumer engagement. Each of these actions, though, relies on the measurement, collection and processing of a large variety of data. However, a proper framework for big data analytics in power systems is still missing, as it has been highlighted in IEEE Task Force technical reports [10]. In what follows, a reasonable roadmap for the effective implementation of modern power systems is outlined, and the correlated needs and necessities are identified.

The grid infrastructure needs to be reinforced to guarantee stable and continuous service. Transmission and distribution lines were planned and dimensioned for well-defined and constant power flows. In the presence of high shares of RESs, though, these conditions are no longer valid, and lines are operated under sub-optimal conditions (e.g., close to their ampacity limit). Given the high costs of a full system refurbishment, this congestion phenomena could be solved by coordinating the RESs and by monitoring the grid states at higher sampling rate.

Advanced energy storage solutions can be useful to balance the intermittent power output from most RESs. The most common solution is represented by battery storage systems and super-capacitors. Nonetheless, alternative options such as pumped hydro, compressed air, and hydrogen storage are worth investigating. In recent years, distributed generation has made possible the development of small energy communities, capable of operating as small islands, but still connected to the main network. A similar approach would allow for maximizing the efficiency of the distributed generation sources, however, requires constant and efficient coordination between the different parts of the network.

Based on this list of trends and needs, it is worth observing how the modernization of power systems relies on a preliminary implementation of a novel and effective monitoring and control infrastructure. This can be achieved only via a distributed and capillary data acquisition system. To the state of the art, the control rooms and the system operators are not ready to cope with such an amount of data and information [11] and [12]. Nevertheless, data analytics is already essential for enhancing the efficiency, reliability, and sustainability of power systems. Beyond this initial realization of data analytics, it is reasonable to expect that data analytics will enable better and deterministic decision-making, optimize operations, and facilitate the integration of renewable energy, ultimately con– tributing to a more resilient and responsive grid.

3.1. Ancillary services

Ancillary services are required to maintain frequency, voltage, and system security in real time. Their purpose is to ensure stable operation during normal conditions and to manage disturbances. In low inertia power systems (LIPS) these same services are still needed but must operate with faster response times, higher precision, and often with explicit locational or dynamic requirements.

Frequency control services exist to maintain system frequency within acceptable limits by continuously balancing generation and demand. Their purpose is to contain frequency deviations immediately after a disturbance and to restore the system to normal operating conditions. The primary reserve stabilizes the frequency by providing a continuous, and often proportional, active power response, while the secondary reserve restores the frequency to its nominal value and re-establishes reserve margins. Under low inertia conditions faster ancillary services, notably fast frequency response (FFR) and synthetic inertia therefore become essential to ensure frequency stability. As inertia declines, these services also play a crucial role in providing sufficient damping of the system frequency.

Voltage control services maintain stable voltage levels through reactive power support and dynamic voltage regulation. They can broadly be divided into static and dynamic voltage services, each serving different purposes but both essential for secure operation. Static voltage service provides steady state reactive power support and regulates voltage under normal operating conditions. The function is to maintain voltage profiles, compensate for reactive power flows, and manage slow variations in system loading. Static services include reactive power capability from generators, capacitors, reactors, and other devices designed to maintain the voltage within planned limits. In low inertia systems, the underlying need for static reactive power remains the same, but the voltage may be more sensitive to variations as reactive power change. This increases the importance of ensuring that static reactive power is available at smaller steps and at the right location since the effectiveness of reactive support is even more location dependent on weak grids. Dynamic voltage service provides dynamic reactive power support and voltage control during disturbances or fast voltage changes. The purpose is to support voltage recovery as a dynamic response and contribute to e.g. transient stability after faults or sudden power imbalances. The service is typically delivered by synchronous machines, synchronous condensers, STATCOMs, and converters. In LIPS, the need for dynamic voltage support becomes more pronounced as disturbances can lead to faster and deeper voltage dips. As a result, dynamic voltage controllers may need to operate with shorter response times and higher bandwidths but that may increase the risk of resonance and instability.

Fault current services support system protection and voltage during faults by providing short-circuit current. In conventional power systems, synchronous machines inherently supply high fault currents. In low inertia and converter-dominated systems, however, fault current contribution is significantly lower. Fault current in converters is not inherently provided but can be provided by converters through control.

3.1.1. IBRs Structures: Grid Following (GFL) and Grid Forming (GFM) converters.

An increasing share of ancillary services in modern power systems is delivered by converter-based resources, whose capabilities depend strongly on their control structure. Grid following (GFL) converters operate by synchronizing to the grid voltage using a Phase-Locked Loop (PLL). Hence, they rely on the existing voltage waveform and system strength at the point of connection to remain synchronized. In modelling terms, GFL converters behave as controlled current sources with high output impedance, injecting current according to an externally imposed voltage reference. However, GFL converters can already contribute to several ancillary services, including dynamic reactive power control to support the voltage, and FFR. GFL can also provide fault ride through (FRT) capability and fault current injection, though this is strictly limited by the converter's semiconductor rating (typically 1.1–1.2p.u.). However, GFL's ability to contribute to system strength is constrained. In weak grids with a low SCR, PLL-grid interactions can lead to instability and oscillations.

Grid forming (GFM) converters, in contrast, create their own internal voltage and frequency reference and can therefore operate independently of system strength. GFM are typically modelled as voltage sources behind a virtual impedance and can set or stabilise the local voltage waveform and strength. GFM can, as for GFL, also supply limited fault current injection. GFM maintain stable operation during grid disturbances without relying on strong voltage waveforms. These characteristics make GFM converters central for providing the ancillary services in weak and low-inertia grids, particularly for frequency stability, system strength, and robust dynamic voltage response. Using control strategies such as droop control or Virtual Synchronous Machine (VSM), GFM can emulate the swing equation of a synchronous machine.

4. Enabling technology for rapid data acquisition and information extraction

Wide area monitoring systems (WAMS) are the technology in the transmission system enabling rapid acquisition and information extraction and play a key role in the management and control of modern power systems. WAMS are a collection of several PMUs in a coherent region, streaming the measured data to a phasor data concentrator (PDC), where data stream is sorted and timestamped. WAMS use high-speed communication infrastructure that can vary from optical fiber cables, power line carries, mobile technology networks (4G/5G) and satellite communication. In the following subsections, the challenges related to PMU and WAMS systems as well as new emerging data acquisition technology such as Point-on-wave (PoW) measurement units are also described.

Fig. 6 displays an architectural diagram of the Hierarchical Wide Area System Monitoring System. It illustrates the three-tiered structure

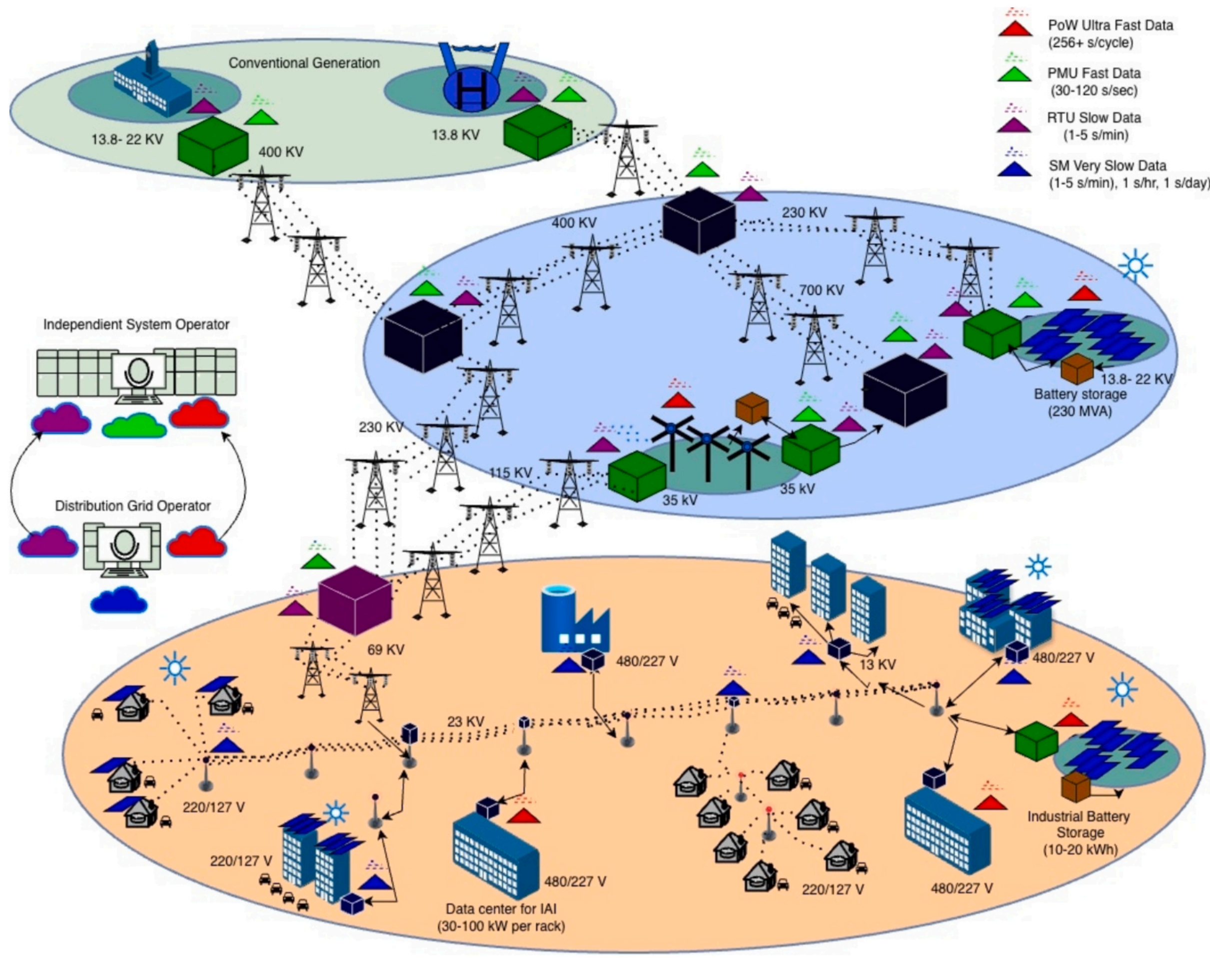

Fig. 6. Wide-area monitoring system architecture, where the different layers of the system are indicated.

and shows how data from Point-on-Wave (PoW) measurement, Phasor Measurement Units (PMUs), Remote Terminal Units (RTUs) and Smart Meters (SMs) flows from the local grid edge to the central control centre, where it is used for comprehensive grid analysis and management. PoWs are installed at specific points of interest at high-voltage transmission substations with renewable generation, or at low-voltage distribution system points where critical loads such as data centres are connected. With PoW sampling waveforms at 256 samples per cycle or more, transients and other phenomena can be accurately recorded. This technology is important as the power system transitions towards power electronics technologies, such as those embedded in renewable resources. PMUs are installed at critical high-voltage transmission substations and large generation points. Synchronised measurements of voltage, current, phase and frequency at high sampling rates (10–120 samples per second) are collected and processed to characterise low-frequency oscillations and transient stability events. Meanwhile, the RTU is connected to the SCADA system, maintaining a sampling frequency of between one and five samples per minute. The RTU collects unsynchronised data from high-voltage transmission and low-voltage distribution substations for monitoring and feeding applications in power system control (state estimation, power flow, optimal power flow and aggregated load consumption energy). Finally, the SM collects unsynchronised data (1–5 samples per minute, 1 sample per hour, 1 sample per day) from the low-voltage distribution systems, specifically of conventional load consumption energy (residential, commercial, public lighting and industrial) and more recently sectors integrating DERs and data centers for AI. The SM belongs to the Advanced Metering Infrastructure (AMI) system, which is used to monitor the distribution system.

4.1. PMU accuracy

PMUs measure voltage and current phasors, frequency and rate of change of frequency based on an absolute time reference for phase angle evaluation [13]. Such absolute reference is typically provided by coordinated universal time (UTC). Each PMU provides synchronized phasors (the so-called synchrophasors): they follow the evolution of the phasor state over time, monitoring voltage and current signals at the fundamental frequency. Thanks to the high rate of measurements, up to 120 measurements per second, PMUs can follow the signals also in the presence of changes in the operating conditions. Specifically, the PMU algorithms are designed to follow possible dynamics in the signals of interest, but these dynamics must be slow compared to the system frequency. PMU performance is typically evaluated through various indices. The most used index is the total vector error (TVE), represented as a percentage, i.e. the absolute value of the relative vector difference between the measured synchrophasor and the reference one. This index provides cumulative information on the measurement performance of amplitudes and phase angles. The other adopted indices are related to frequency error (FE) and the Rate Of Change Of Frequency (ROCOF) error (RFE).

The PMU standards provide different limits for TVE depending on the performance class and the test conditions, see [13,14]. Specifically, this latest standard, in continuity with what is described in the previous standards, reports specific tests for steady-state and dynamic conditions. It must be highlighted that the tests for dynamic conditions are necessarily limited and consider one phenomenon at a time. In this regard, it is worth noticing that "all compliance tests shall be performed with all parameters set to standard reference conditions, except those being varied as specified for the test" [13]. The standard 60255-118-1 assumes as reference conditions constant rated voltage and current magnitude and constant nominal frequency; total harmonic and noise distortion must be less than 0.2 % of the specified test level; all interfering signals must be less than 0.2 % of the fundamental component [13].

However, several factors can affect the quality of the measurements, such as changes in the signal or the presence of disturbances, but, in general, the operating conditions in which the PMUs are immersed while providing measurements are not evaluated in real-time. Consequently, performance indices should first be evaluated through tests under laboratory-controlled conditions, where the characteristics of the test signal can be used to describe the reference value used for performance determination. Once in the field, PMUs work under realistic operating conditions where the true signal is no longer available, and the only information that can be used to determine measurement accuracy typically refers to manufacturers datasheets, which should comply with the specifications described in the standards.

Therefore, the association of field measurements with the corresponding uncertainty is a critical phase. Certainly, it is important not to underestimate but neither overestimate the data uncertainty. In this context, it should not be forgotten that PMUs are typically downstream of instrument transformers, typically inductive, whose behaviour is described only at the fundamental frequency. A complete characterization of instrument transformers in the presence of realistic signals is typically not available from manufacturers and must be specifically requested. During severe inverter-driven transient events such as the 2016 Blue Cut Fire in California where large amounts of solar PV got disconnected due to the tripping of several transmission lines, sudden phase jumps could confuse PMU algorithms, causing them to incorrectly report massive frequency drops or collapses while actual system frequency remained within normal bounds [15]. Therefore, a critical point to ponder when considering PMU measurements in LIPS is the measurement traceability and uncertainty, particularly critical factors in the presence of dynamic signals. A study on the challenges, due to test descriptions and error boundaries, of monitoring real dynamic signals with PMUs has been presented in [16].

4.2. PMU latency

One of the critical aspects in the design and implementation of WAMS and WAMPAC systems is the total latency, i.e., the time delay between the occurrence of an event in the electric system and the execution of associated management and control actions. Latency can greatly affect overall system performance, with possible implications for the safety, reliability, and stability of the grid. Therefore, it is useful to evaluate the latency of each element within the monitoring and control chain. In this regard, it would be beneficial to propagate time properly across the entire network infrastructure [17,18]. Depending on the implemented algorithm, PMUs can introduce considerable delay into WAMPAC systems, and, for this reason, the literature has focused on their latency characteristics and requirements. The design and implementation of a measurement platform that allows latency characterization of different types of WAMPAC systems in several operating conditions was presented in [19]. The characterization of PMU latency was analyzed as well in [19].

4.3. PMU bandwidth and filters

The standard IEC/IEEE 60255–118-1 defines a set of possible PMU reporting rates which range from 10 to 100 or 120 frames per second for 50 and 60 Hz nominal system frequency, respectively. As a consequence PMUs produce measurements of fundamental magnitude, phase, frequency, and ROCOF with an update rate in the order of few tens of ms. Following the Nyquist theorem, this limits the maximum frequency of the dynamics which could be captured by the PMUs. For this reason, slower reporting rates are typically used for long-term monitoring applications, while faster reporting rates can be used to track rapid variations in any of the measured quantities. In fact, the standard IEC/IEEE 60255–118-1 includes the possibility to change the PMU reporting rate in correspondence of a UTC full second transition, such that no packet loss occurs during such operation.

PMUs are typically installed at the secondary output of instrument transformers, i.e., a set of either voltage or current transformers (briefly, VTs and CTs), which convert the power signals into low-voltage or low-current signals compatible with the PMU analog front-end. In this sense, the measurement chain of the PMU can be summarized as the cascade of three consecutive stages: the instrument transformer, the digitizer, and the processing stage. In first approximation, each stage can be approximated as a bank of filters which limits the spectral content of the input signal. The rigorous characterization of these filters' characteristics (e.g., magnitude and phase errors, group delay, impulse response) is crucial to guarantee that the measurement system is capable of tracking fast dynamics with sufficient accuracy and responsiveness.

In general, PMUs were conceived and designed to focus on the fundamental component only. In this sense, harmonic and interharmonic components were considered as disturbances and were filtered out during the measurement process. In recent years, the rising attention given to power quality phenomena has driven the development of enhanced PMU algorithms which are capable of estimating also harmonic and interharmonic phasors with remarkable accuracy. This comes evidently at the cost of higher computational complexity, but represents a natural extension of PMU-based measurement systems and paves the way for their integration with other instruments like Power Quality Instruments and Smart Meters.

4.4. Point-on-Wave / waveform measurement units (WMUs)

Point-on-wave (PoW) measurement units, also referred to as waveform measurement units (WMUs), represent an advancement in power system monitoring technology. Unlike the traditional PMUs PoW/WMUs capture the details of electrical waveforms as they occur in real time. This difference offers more granular insight into grid dynamics and disturbance monitoring. WMUs measure directly on the waveform, including the deviations from the ideal sinusoidal shape, tracking the instantaneous values of voltage and current at high sampling rates. This

Table 1
Main differences between PMUs and PoW devices.

Characteristics	PMU Devices	PoW Devices
Sampling time	30–120 samples/sec	Typically 48 k–96 k samples/sec
Time-synchronization	Yes	Yes
Data storage	In the range of GB	In the range of TB
Performance during fast phenomena (transients)	Incorrect phasor representation during fast phenomena (transients) leading to incorrect measurements or not recording at all	High resolution and accuracy during fast phenomena (transients)

contrasts with PMUs, which estimate the phasor representation as the magnitude and phase angle of a sinusoidal waveform over multiple cycles. As mentioned, PMUs are highly effective for monitoring long-term stability and slower phenomena, while WMUs are ideal for fast-evolving phenomena in the grid. A summary of the main differences between PMUs and PoWs are displayed in Table 1. The granularity of data provided by PoW/WMUs aligns closely with the outputs of electromagnetic transient (EMT) simulations, which model the power system at the level of individual waveform cycles. EMT simulations are essential for studying fast-switching devices, inverter-based resources (IBRs), and other components where small deviations in the waveform can have large operational impacts. WMUs enable real-world measurement of the same types of phenomena modelled in EMT studies, providing a bridge between simulation and real-time data. The high-resolution measurements from WMUs generate a large amount of data, far exceeding what is captured by PMUs. The volume of data captured by PoW/WMUs calls for advanced big data analytics techniques to extract meaningful information and insights. Data analytics applied to synchro-waveforms opens new possibilities for condition monitoring, fault detection, preventive maintenance, and grid stability analysis.

4.5. POW sensors vs WMU: Market available product-oriented outlook from industry

As described above, unlike PMUs, which output calculated phasors, POW sensors capture the raw, high-resolution analog waveform (often 256 + samples per cycle, or upwards of 15 kHz). POW is vital for observing the sub-cycle, fast-switching transients of power electronics. Because they do not assume the grid is a perfect sine wave, POW measurements are required to analyze high-frequency wideband oscillations (up to kHz ranges) caused by inverter control loops interacting with weak grids. However, the data footprint of POW measurement infrastructure is staggering. A single three-phase POW sensor can generate billions of data points per day. Continuous transmission of this data is often impossible, so real-world deployments rely heavily on edge computing, i.e., processing the data locally and only transmitting the anomalies.

In several industry specific applications, WMUs becomes a market-available product-oriented term because WMU acts as a realistically implementable bridge between the theoretical conceptualization of the phasor-only PMU and the data-heavy POW. WMUs provide continuously synchronized waveform data at a manageable rate (e.g., 200 samples per second). For LIPS application, WMUs are highly specialized for detecting Sub-Synchronous Oscillations (SSO). For example, in the UK's VISOR project [20], WMUs were deployed specifically to monitor SSO in the 4 to 46 Hz range—a growing risk when integrating large offshore wind farms, HVDC links, and series capacitors. However, WMUs face real-world challenge of achieving the microsecond-level synchronization which is required to correlate waveforms across wide-area scale. Furthermore, standardizing the data format and ensuring interoperability among different WMU vendors remains a challenge for system operators.

4.6. Digital fault Recorder (DFR)

DFRs are event-driven devices designed to capture high-resolution electrical waveforms specifically during fault conditions (e.g., short circuits, lightning strikes).In LIPS, as IBRs replace traditional generators, fault currents become much lower and harder to detect. DFRs are critical for post-mortem analysis to understand exactly how an inverter's protection systems reacted during a fault. They are also heavily used for Traveling Wave Fault Location (TWFL), pinpointing line faults to within a few hundred meters. However, because DFRs are trigger-based, setting the correct thresholds is notoriously difficult. If thresholds are too high, the device misses the fault; if they are too low, the memory fills up with “nuisance” triggers from minor grid fluctuations.

4.7. Voltage disturbance Recorder (VDR)

A VDR (sometimes called a Voltage Dip Recorder) is a simpler, often plug-in diagnostic logger that records discrete power quality events like sags, swells, impulses, and outages. For LIPS, VDRs are primarily used at the distribution edge or facility side. In weak grid, slight transmission faults can cause deep, momentary voltage sags that trip sensitive industrial equipment. VDRs provide a cost-effective, first-line diagnostic tool to prove whether a disturbance originated from the utility side or the facility side. However, VDRs lack the wide-area synchronization of PMUs/WMUs and the high fidelity of POWs. They are isolated, reactive troubleshooting tools rather than proactive grid-monitoring assets.

Table 2 provides a performance comparison matrix for the above-mentioned monitoring devices.

With respect to the taxonomy of stability phenomenon in LIPS from Fig. 3, monitoring devices find their applications in several analysis to detect potential instabilities of different sub-categories [21] as it is summarized in Table 3.

Table 2
Performance comparison of different monitoring devices.

Device	Primary Output	Typical Sampling Rate	LIPS applications	Data footprint	Dominant source of error
PMU	Synchrophasors (Magnitude, angle, frequency)	30 – 120 frames/sec	Macro-stability, ROCOF, inter-area oscillations monitoring.	Moderate (continuous).	*High (Algorithmic)*: TVE spikes due to DFT windowing and filtering delays during fast step changes or wideband oscillations.
WMU	Synchronized continuous waveforms	~200 samples/sec	Sub-synchronous oscillation (SSO) tracking.	High (continuous).	*Low (Hardware/Synchronization)*: Minimal algorithmic error; primary errors are from timing jitter and instrument transformer bandwidth limits.
POW	Raw time-domain waveforms	15,000 + samples/sec	Inverter transients, high-frequency resonance monitoring.	Massive (often processed at the grid edge).	*Very Low (Hardware)*: Captures true dynamics; errors restricted to CT/PT saturation or ADC quantization noise.
DFR	Fault waveforms beyond triggering threshold	Fast (kHz) during events	Post-fault analysis, protection validation.	Low (Event-based).	*Moderate (Transducer)*: DC offsets and severe Current Transformer (CT) saturation during faults distort the raw waveform.
VDR	Threshold events (Sags, swells, outages)	Event-based logging with internal ADC output at 128 to 1024 samples per cycle with 2 to 5 cycles before the event and a few cycles during and after.	Localized power quality diagnostics.	Very Low (Event-based).	*Moderate (Algorithmic)*: Half-cycle RMS calculation loses accuracy under severe harmonic distortion or rapid phase shifts.

Table 3
Stability category and methodical application of the different technologies.

Stability category		Physical devices	Use cases for methodical applications	Monitoring tools
Rotor Angle Stability	Small-signal disturbance (0.1 Hz to 0.4 Hz)	PMU, DFR	Modal analysis, eigenvalue analysis, system damping characterization, small signal stability analysis, power oscillations detection.	Online DSA, WAMS.
	Transient Stability	PMU	RMS analysis, energy functional criteria (i. e. Lyapunov stability analysis).	Online DSA, WAMS.
Voltage Stability	Small-signal disturbance	PMU, WMU, VDR, DFR	Small signal stability analysis.	Online DSA, WAMS.
	Large-signal excitation	PMU	Voltage collapse/increase algorithms, RMS simulations.	Online DSA, WAMS.
Frequency Stability	Short-term	PMU, DFR, FDR	RMS simulations.	Online DSA, WAMS.
	Long-term	PMU	RMS simulations, Single-machine equivalent (SME) or center of inertia (COI) model-based analysis.	WAMS.
Resonance Stability	Electrical	High sampling rate PMU, DFR, WMU	Impedance based analysis tools, frequency response analysis tools, EMT simulations.	Sub-synchronous Resonance (SSR) detection and mitigation systems (i. e. filters).
	Torsional	High sampling rate PMU, DFR, WMU	EMT simulations.	Online torsional resonance monitoring.
Converter-driven Stability	Slow interaction (less than 10 Hz)	PMU, DFR, WMU	Modal analysis, eigenvalue analysis, small signal stability analysis.	Advanced WAMS monitoring, Online DSA.
	Fast interaction (above 10 Hz, can be upto100 Hz or higher)	High sampling rate PMU, DFR, WMU	Modal analysis, eigenvalue analysis, impedance-based analysis tools	Advanced WAMS monitoring.

5. Challenges for control and assessment in Low-Inertia power systems

The transition to LIPSs introduce challenges at the different voltage levels: the extra high voltage level or transmission systems (TSs) and the low voltage level or distribution systems (DSs). Some of these issues are similar or the same among the different voltage levels. Fig. 7 summarize the most important topics and in this section a brief description of them is provided.

5.1. Operational challenges

In the planning phase, it is essential to analyze and define the secure operating ranges of key system variables such as inertia, grid strength, grid impedance at the point of common coupling and dynamic voltage control. Detailed studies e.g. by electromagnetic transient (EMT) simulations are necessary to understand the secure conditions under which the system can operate. These studies must establish the conditions, for example, minimum inertia levels and grid strength required for stability, assess grid impedance and evaluate the system's ability to provide dynamic voltage control. Grid strength should be assessed to ensure the grid can handle dynamic conditions and disturbances effectively. Additionally, reinforcing the grid may be necessary to support various shares of RESs. Available mitigation measures, such as ancillary services, must also be integrated to ensure system stability and support in critical moments. During or close to operation, tools must be in place to ensure that these predefined secure conditions are maintained. This requires real-time monitoring and forecasting to continuously assess inertia and other critical system variables. If monitoring systems detect those secure operating conditions are not being met, or forecasted to deviate, operators must have the possibility to take corrective actions. Without accurate observability and forecasting, operators may lack a clear understanding of the system's current state, leading to delayed responses or reactive measures that could compromise system stability. Indeed, TSs and DSs differ significantly in terms of crucial variables such as power flow, load variability, line length, etc. It is thus realistic to expect that low-inertia affects them differently, based on the different roles they play in the overall power grid [22,23].

In addition to the technical challenges that arise from the expected implementation of big data applications, the role of humans operating a highly automated power system to ensure safe and efficient grid operation is often not considered. As this consideration is not part of this paper, the authors refer to the detailed discussion in [24]. In the following, the major challenges are grouped according to the system they are likely to affect most significantly.

5.2. Distribution system challenges

In recent years, DSs have hosted an ever-increasing number of DERs (e.g., rooftop solar system, small battery storage systems, electric vehicles, etc.). This poses several challenges in terms of congestion management and the control of the power flow. These resources are volatile and provide negligible compensation in terms of reactive power. Moreover, they are distributed in a capillary way and usually cannot be controlled directly by the system operator, except in Germany, where sources larger than 25 kW have to be controllable. To regulate their use and minimize their potential disruptive effects, it is necessary to introduce more stringent constraints on the installation requirements and more tailored energy tariffs based on the specific power flow in the grid [25].

Most RESs depend on natural phenomena that may be volatile and intermittent. As a result, their power output is also characterized by sudden variations and voltage fluctuations. This makes the installation of voltage regulators, capacitors and on-load tap changers necessary, with the consequent inevitable increase in the maintenance costs for the system operator. The inverters rely on a power electronic circuitry switching at high frequencies. In the power conversion, such a mechanism produces a significant harmonic and inter- harmonic pollution of the output signal [26]. These spurious components may interfere with the monitoring and metering infrastructure. Moreover, in the long term, they can cause overheating and damage to some grid components or connected appliances [27]. In addition, harmonics and power quality issues can also cause maloperation of protection. A significant factor in the grid to handle harmonics is the grid strength characterized by a low short-circuit ratio and voltage stiffness. In strong grids, harmonics are often absorbed or dissipated without significant impact. However, in weak grids, reduced damping capabilities make distortions more severe. In the absence of synchronous generators in the vicinity, which provide

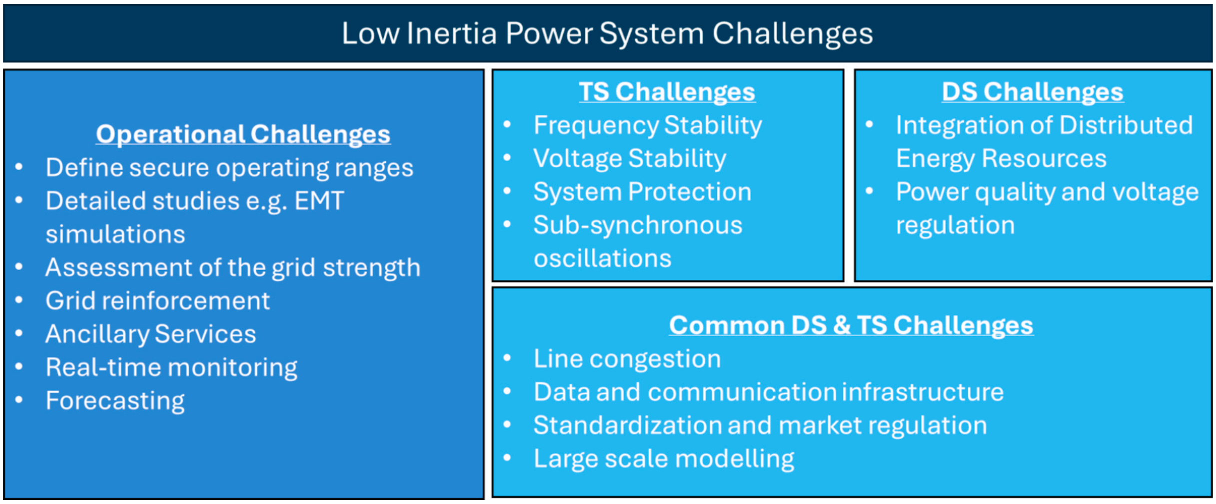

Fig. 7. Challenges for control and assessment of low-inertia power systems.

inertia and short-circuit power distortions are more likely not to dampen and may propagate further. Although converters can be controlled to mitigate harmonic issues by implementation of active filtering through control, which aims to absorb harmonics, their effectiveness is often limited in low- strength grids.

5.3. Common challenges in distribution and transmission systems

The transmission system challenges listed in Fig. 7, were introduced in Section 2 and in this section, the issues that overlap on both voltage levels are now discussed. One of the rising problems that affect both system levels is line congestion. In power systems theory, the concept of line congestion occurs when the power demand exceeds the capacity of the lines (i.e., the capacity of the conductor). Moreover, the inherent variability and geographical distribution of RESs tend to exacerbate this issue. On one side, their power output is volatile and unpredictable. On the other side, they are often located far from urban areas, i.e. far from the major load centers [28].

The monitoring infrastructure currently deployed in TSs and DSs is not ready to support all the metrics and indicators needed to control the RESs integration. This aspect involves not only the communication infrastructure in terms of servers and protocols but also the processing capacity in the control room. Even equipping each substation with sophisticated monitoring devices, the current procedures for grid protection and control are not ready to integrate such a massive and diverse set of data and information [29].

In this regard, another issue is surely represented by the cybersecurity concerns. The energy market is a potential target for many malicious attacks. Therefore, the idea of stream- ing such delicate information over traditional communication means requires a preliminary assessment of the capability of promptly detecting and rejecting any possible external intervention [30].

The existing framework in terms of normative and market regulations is not designed to cope with low-inertia power systems. Indeed, from a normative perspective, the current performance requirements in terms of accuracy and latency are not intended for power systems with high shares of RESs. It is likely that these requirements shall be updated and tightened in order to reflect the more challenging conditions of this new scenario (particularly in terms of responsiveness and higher resilience against distortion).

Similarly, the market regulations also need to be modified. Currently, the operators have the opportunity to set hourly tariffs that may encourage consumers to adopt more convenient power profiles. However, in the presence of large shares of DG, the market regulation lacks a proper tool for synchronizing the different production units and guaranteeing a safe operation in terms of voltage stability and line congestion [31].

One of the critical challenges of analyzing the stability and security of power systems with high penetration of RES is the proper modelling of system components [32]. The integration of accurate models is essential to ensure reliable simulations [33]. However, manufacturers often provide black-box models for IBRs and other advanced grid components, which limit transparency and flexibility in simulation studies. In addition, this increases the risk of unobserved issues under various operating conditions, leading to uncertainties in stability and security assessments. To capture properly the system dynamics EMT simulations are often required; however, simulating large-scale systems in EMT software is time-consuming and computationally expensive. It also becomes challenging to simulate numerous combinations of grid conditions, power flows, and fault scenarios due to the complexity of the models.

6. Potential solutions to low inertia power system challenges

To address the challenges introduced in Section 5, it is necessary to develop new control protocols, capable of dealing with much faster and stronger disturbances. Such a paradigm change can be achieved via different technological and methodological solutions, which will be briefly summarized in the following paragraph. Nevertheless, it is important to underline that each solution should be customized to the particular characteristics of the grid under analysis. There are no predefined recipes to guarantee the continuity and quality of service. Only a deep knowledge of the grid behaviour in the different operating conditions may allow for properly dimensioning the control protocols and mechanisms.

LIPS are subject to sudden imbalances between generation and load, which have an immediate impact on the system frequency. Most control algorithms rely on the measurement of the ROCOF, the frequency time derivative. Indeed, they exploit the inherent predictive behaviour of the derivative term to catch in time potential disruptive events. However, in LIPSs, ROCOF may experience rapid and large oscillations, losing its primary significance [34]. In recent years, the estimation of frequency and ROCOF has been largely improved, both in terms of accuracy during dynamic events and robustness against interfering components [35]. Nonetheless, a primary objective for power system operators is to keep a stable frequency value by dampening any power imbalance as fast as possible. In this sense, different solutions can be implemented on different time scales. During transient events, the so-called Fast Frequency Response (FFR) allows injection or absorption of power for a short amount of time (e.g., using batteries or demand-response mechanisms). During normal operation, instead, it is possible to program the inverters' power electronic circuitry such that they emulate a sort of "synthetic inertia". Synthetic inertia reduce the ROCOF variation range but need fine-tuning and a coordinated approach among the different actors in the grid [36].

Unlike synchronous generators, IBRs do not provide automatic control of the active and reactive power balance, as presented in Section 3. It is thus necessary to install devices capable of compensating for the amount of reactive power sufficient to guarantee a stable voltage level. In a similar way to the previous paragraph, there exist different solutions for different time scales. Dynamic voltage regulators are devices capable of providing immediate support during transients by injecting or absorbing re- active power. Conversely, static VAR compensators are devices capable of adapting the reactance of the system adaptively. In this way, they help maintain voltage levels during load changes and disturbances, improving voltage stability [37].

From an operational perspective, one of the most challenging aspects is the automation of the control actions. The monitoring infrastructure currently deployed on the grid is inadequate and insufficient to capture and track such rapid and strong dynamics to take automated and coordinated control actions. A full renovation is needed to achieve the accuracy and responsiveness of a few tens of milliseconds. In this sense, PMUs may represent the most viable and promising solution. Based on their traceable time-stamp, it is possible to compare measurements from different nodes and carry out useful routines such as state estimation and fault location with refresh rates in the order of hundreds of frames per second [38–40]. A real game-changer would be represented by implementing distributed control through coordination among the inverters deployed in different parts of the grid. The so- called Grid Forming Converters (GFM converters) promise to have a strong impact, thanks to their capability of enhancing grid stability and improving power quality [41]. However, their impact is deemed to remain ineffective if each converter operates in a sort of islanded mode. It is necessary to develop distributed computation and control strategies that sets the optimal response from a network of GFMs. This poses several challenges from both a methodological and technical perspective. On one hand, the problem is highly non-linear and the response of the power system is hard to predict especially in the presence of high shares of IBRs. On the other hand, in the same grid it is likely to find GFM converters from different manufacturers, with different features and specifications. Apart from the communication and interoperability issues, the control strategy should be able to take into account the characteristics of each single converter when finding the global optimum for the entire system [42]. A compilation of data-driven solutions with explicit methods and examples can be found in [43].

7. Conclusions and future outlook

The transition to low-inertia power systems is no longer a future possibility but an operational reality and necessity. As synchronous generation is progressively displaced by inverter-based resources, the dynamic behaviour of modern power systems is being fundamentally altered. This work has shown that the consequences extend well beyond the traditional concerns of frequency, voltage and rotor-angle stability. Converter-driven interactions, resonance phenomena, reduced fault-current levels, faster transients and weaker system strength are now defining features of grid operation. As a result, the secure operation of future power systems cannot rely on conventional practices alone but requires a broader, more integrated framework that combines advanced monitoring, improved modelling, fast control and coordinated ancillary services.

Our conclusion is that observability will be a key enabler of resilience in low-inertia power systems. Hierarchical monitoring architectures based on PMUs, WMUs/PoW devices, DFRs, VDRs, RTUs and smart meters can provide complementary visibility across temporal and spatial scales. However, measurement availability alone is insufficient. The full benefit of these technologies depends on measurement accuracy, traceability, latency, interoperability, cyber-secure communication and the ability to transform large volumes of heterogeneous data into meaningful operational knowledge. In this respect, wide-area monitoring systems, supported by advanced data analytics and digital-twin-based decision-support tools, are expected to become increasingly important for situational awareness, early warning, stability assessment and corrective control.

The future operation of low-inertia power systems will require a paradigm shift in control and coordination. Fast frequency response, synthetic inertia, dynamic voltage support, storage systems, demand response and grid-forming converters are expected to play key roles in maintaining system stability. Yet their effectiveness will depend on system-wide coordination rather than isolated deployment. Future grids will therefore require closer interaction between transmission and distribution system operators, updated operational practices, and regulatory and market frameworks that can value fast, location-dependent and stability-oriented services. At the same time, the increasing complexity of converter-dominated systems will demand more transparent and validated models, particularly for electromagnetic transient behaviour and controller interactions under weak-grid conditions.

Looking ahead, several priorities emerge. These include developing accurate, scalable modelling approaches for inverter-based resources; improving methods for assessing stability across multiple time scales; harmonising standards for high-speed monitoring under realistic operating conditions; and developing robust, data-driven methods based on artificial intelligence and machine learning for prediction, diagnosis and preventive control. In this context, AI/ML-based solutions are expected to play an increasingly important role in low-inertia power systems, particularly in extracting meaningful information from large volumes of heterogeneous measurements, identifying early signs of instability, supporting adaptive protection and control, and enabling faster, more reliable decision-making. With the increasing availability of high-performance computing platforms and cloud-scale computational infrastructure, many of these advanced data-driven solutions can be implemented in real time, thereby enabling practical online applications in monitoring, assessment and control. Particular attention should also be given to the use of artificial intelligence in a trustworthy, robust and explainable manner; the coordinated operation of mixed fleets of grid-following and grid-forming converters; and the integration of human operators into increasingly automated control environments. Ultimately, the path towards resilient low-inertia power systems will not be defined by a single technology, but by the successful integration of monitoring, analytics, communications, control, regulation and market design. In that context, WAMS-enabled, data-informed and interoperable control platforms are likely to become a cornerstone of secure, sustainable and resilient power system operation.

CRediT authorship contribution statement

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review & editing, Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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