Technical Report

Instability Detection Technologies in Power Electronics Dominated Systems

January 2026

entsoe

Foreword

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association of the European transmission system operators (TSOs). The **40 member TSOs, representing 36 countries,** are responsible for the secure and coordinated operation of Europe's electricity system, the **largest interconnected electrical grid in the world.**

Before ENTSO-E was established in 2009, there was a long history of cooperation among European transmission operators, dating back to the creation of the electrical synchronous areas and interconnections which were established in the 1950s.

In its present form, ENTSO-E was founded to fulfil the common mission of the European TSO community: to power our society. At its core, European consumers rely upon a secure and efficient electricity system. Our electricity transmission grid, and its secure operation, is the backbone of the power system, thereby supporting the vitality of our society. ENTSO-E was created **to ensure the efficiency and security of the pan-European interconnected power system** across all time frames within the internal energy market and its extension to the interconnected countries.

ENTSO-E is working to secure a carbon-neutral future. The transition is a shared political objective through the continent and necessitates a much more electrified economy where sustainable, efficient and secure electricity becomes even more important. **Our Vision: "a power system for a carbon-neutral Europe"*** shows that this is within our reach, but additional work is necessary to make it a reality.

In its Strategic Roadmap presented in 2024, ENTSO-E has organised its activities around two interlinked pillars, reflecting this dual role:

- "Prepare for the future" to organise a power system for a carbon-neutral Europe; and
- "Manage the present" to ensure a secure and efficient power system for Europe.

ENTSO-E is ready to meet the ambitions of Net Zero, the challenges of today and those of the future for the benefit of consumers, by working together with all stakeholders and policymakers.

* https://vision.entsoe.eu/

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1 Executive Summary

The stability of power systems is crucial for ensuring a continuous and reliable electricity supply, which is key in enabling a competitive and decarbonised European economy. The progressive integration of power electronics interfaced devices (PEIDs), alongside the gradual phasing out of directly connected synchronous machines, presents a transformative stability challenge for Transmission System Operators (TSOs), see Figure 1. This shift necessitates robust instability detection technologies to maintain the reliability and resilience of future power grids.

The "Instability Detection Technologies for System Operators of Power Electronic Dominated Systems" project addresses this need by evaluating various technologies for detecting instability in power electronic-dominated systems. With increased renewable energy sources and the proliferation of PEIDs (in a wide range of assets, from Photovoltaic inverters to High Voltage Direct Current equipment), traditional stability analysis methods may no longer suffice. Instability detection helps mitigate grid disturbances, prevent cascading failures, and maintain operational integrity.

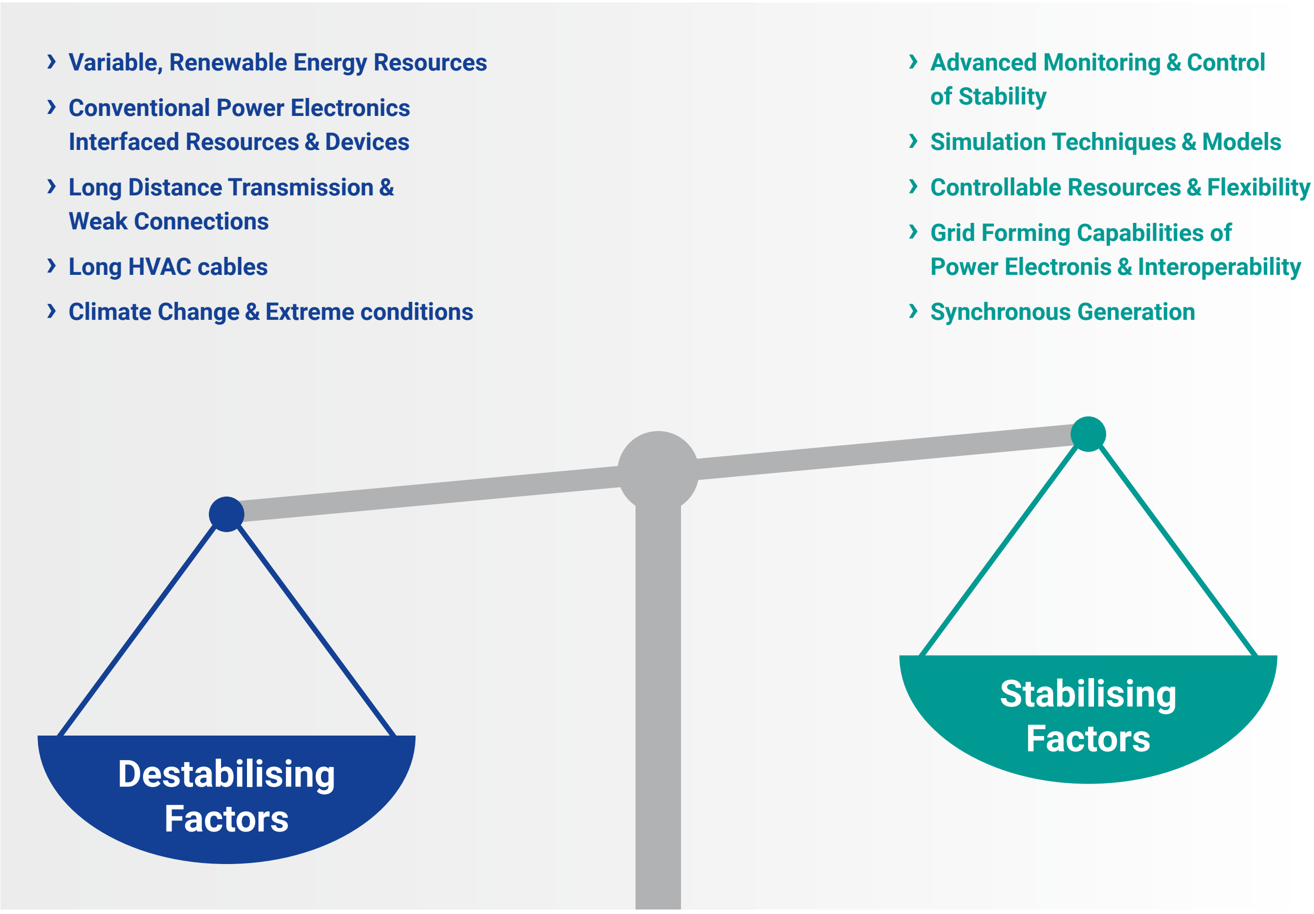


Figure 1: Stabilising and destabilising factors for power grids from ENTSO-E Position Paper on Stability Management in Power Electronics Dominated Systems [1]

This document focuses on the first stabilising factor listed: Advanced Monitoring and Control of Stability. Instability detection technologies that play a key role in monitoring are evaluated and focus on measurement-based technologies and the advancements they will need to keep abreast with the changing power system and stability phenomena.

This report provides an overview of instability detection technologies for power electronic-dominated systems. It explores the strengths, weaknesses, and applications of methodologies like measurement based modal analysis, voltage and current monitoring, Wide Area Monitoring System (WAMS) based on Phasor Measurement Unit (PMU) as well as new means of detection such as Point on Wave (POW) measurements. These insights enable system operators to make informed decisions about grid stability and identify interactions between these devices.

Furthermore, the paper identifies technological limitations related to measurement-based devices (Table 3) currently employed and explores the research needs and relevant stakeholders needed to close the gaps. The paper also investigates some high-level recommendations from the TSO community that would further collective efforts on improving stability detection. By deepening the understanding of instability detection, the paper aims to contribute to the development of a more reliable and resilient power system.

The key takeaways from the technical report are:

- There is a need to further investigate handling, storage and transfer of data from Waveform Measurement Units[1] in an efficient manner
- Standard outputs from measurement-based devices are needed for harmonised data exchange among European TSOs
- Further harmonisation of sensors and measurement techniques is required to ease stability across Europe
- Additional tools are required to tackle growing instability challenges in shorter timeframes. Growing instability challenges are moving towards more challenging timeframes requiring additional tools. Develop an approach for algorithms handling real time analysis
- Need for accurate time synchronisation
- Need for offshore and WAMS implementation standardisation
- Development of criteria for location of PMUs
- Establishment of future approaches to data handling

1 Waveform Measurement Unit (WMU), Synchronised Point-on-Wave (PoW), and Synchronised Waveform are often used interchangeably. For consistency and clarity in this report, we will use WMU as a general term encompassing all these concepts.

2 Background

In response to the challenges identified in the ENTSO-E's RDI Implementation Report [2] under Flagship 5, the Project on "Instability Detection Technologies for System Operators of PE Dominated Systems" was initiated. This tackles critical aspects of the dedicated project concept (10) proposal on Stability Management in power electronics-dominated systems developed by the Working Group 2 – Security and Operation of Tomorrow part of the Research Development and Innovation Committee (RDIC).

The Workstream on Stability Management in Power Electronics Dominated Systems, led by Knut Styve Hornnes, Statnett, was kicked off in April 2021 to develop the said project concept further. A group of experts from RDIC, in close cooperation with System Operations Committee (SOC) experts, developed a workstream description for the Stability Management in power electronics-dominated systems, approved by the RDIC in its meeting on 14 September 2021. It outlines the perspectives of TSOs on research directions to solve technical, operational, regulatory, and market-related challenges for the stability management of the future power system dominated by power electronics. It focuses on developing methodologies, models, tools, and market designs to ensure a stable and reliable future power system. Furthermore, the document considers the current state of technology and research.

At the 18 November 2021 Board meeting, the Board supported the main messages of the stability management workstream description and tasked the RDIC Chair with the involvement of System Operations Committee (SOC), System Development Committee (SDC) and Policy and Communication Group (PCG) to provide a high-level communication paper with a holistic view, describing the challenge at hand. This high-level communication paper would foster a common ENTSO-E understanding of the subject and help to communicate it to decision-makers and other key actors. Committees and the Assembly approved an internal high-level communication paper and a shorter Position Paper in spring 2022, and the shorter version [1] was published on ENTSO-E's webpage in June 2022.

The Position Paper includes:

- Overview of different power system stability phenomena
- Preventive and Corrective actions employed
- The key technological limitations to measurement-based devices currently employed
- Research needs to close current and future gaps regarding measurement-based instability detection devices.
- High-level recommendations from the TSO community to further collective efforts on improving stability detection.

Among the actions presented in the action plan, one aim is to propose methods to predict and monitor system stability and handle controllable resources and flexibility, which are necessary to maintain system stability, system security, and grid resilience, which the current Project is concerned with.

The Project Initiation Document (PID) on "Instability Detection Technologies for System Operators of Power Electronics Dominated Systems" was developed on a cross-committee basis, initiated by the Workstream on Stability Management in PEIDS under WG2, with the aim of forming a cross-committee project team to describe in more detail how to evaluate instability detection technologies and defining criteria for assessing their effectiveness. This will include delving into analysis tools but specifically focus on measurement devices addressing system stability challenges, aiming to highlight needed research and innovation to bridge the gap between current means of tackling stability challenges with the future challenges of a changing power system. The goal is to deliver actionable insights and solutions to empower TSOs in enhancing grid stability and resilience amidst evolving power system dynamics.

The project "Instability Detection Technologies for System Operators of Power Electronics Dominated Systems" was kicked off in March 2024.

Project Objective:

The project's objective is to:

- Identify and evaluate various measurement-based instability detection technologies and techniques applicable to power electronic-dominated systems.
- Provide insights into the strengths, weaknesses, and application methods of these measurement-based instability detection technologies.
- Identify key factors impacting the effectiveness of these technologies.
- Develop guidelines and recommendations for system operators on effective instability detection technologies, considering international standards and publications.
- Identify areas for future research and development in the field of instability detection in power systems.

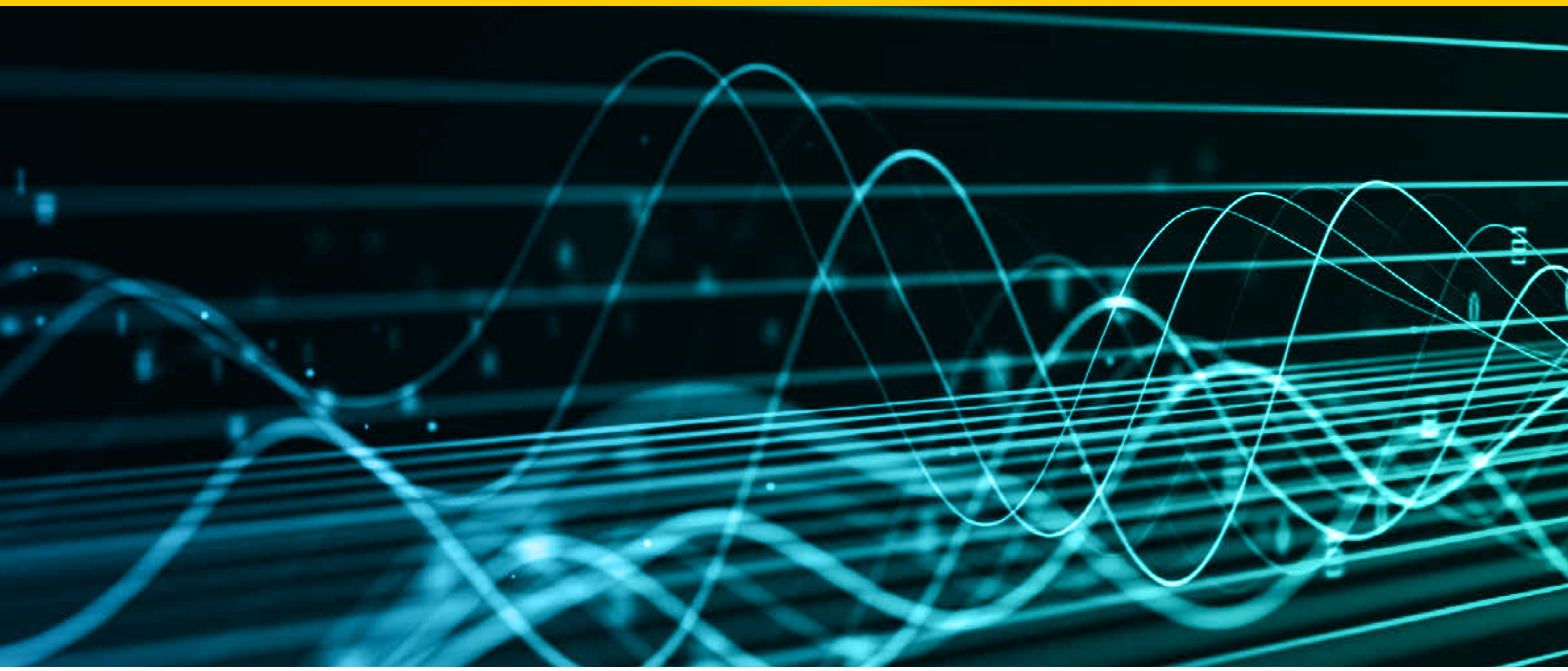
3 Power System Instability Detection Technologies

From prior work within ENTSO-E, the importance and urgence of addressing evolving instability issues as well as new stability phenomena due to a changing power system was made apparent. The position paper Stability Management in Power Electronics Dominated Systems: A Prerequisite to the Success of the Energy Transition [1] highlighted the different risks associated with a changing power system.

Power systems play a key role in ensuring a climate neutral continent by 2050, supporting the increasing capacity of renewable energy sources. This brings stability challenges as power generation will increasingly come from weather dependent and electronically interfaced devices while conventional energy sources will decline, reducing the share of synchronous generators providing inertia. New stability phenomena, alongside changes in existing phenomena, need to be tackled to ensure that the transition to a climate neutral power system is sustainable and successful.

The above-mentioned position paper highlighted the factors that influence system stability, split into destabilising and stabilising factors. This document delves into advanced monitoring and control of stability, in particular, the evaluation of measurement-based instability detection devices and the required research and innovation to tackle changing stability phenomena.

Existing stability phenomena (rotor angle, voltage and frequency stability) are exacerbated by the large number of PEIDs introduced to the power system. Not only have there been a great volume of instability events caused by these phenomena, but the timescale of these phenomena is also reduced. For example, Frequency Containment Reserve must operate in timescales of microseconds to seconds, as opposed to previously seconds to minutes. Monitoring and modelling methods will need to evolve to keep up with these evolving stability challenges and tackle complicated stability management measure for TSOs.



3.1 New Stability Phenomena: converter driven and resonance instability

In 2024 alone Europe installed 16.4 GW of new (gross) wind capacity [3] and 65.5 GW of new solar capacity [4]. The power system is evolving towards networks increasingly using devices with power electronics interface to allow for greater power flow between distant areas (i.e. HVDC links), as well as to provide stability, robustness and controllability of the power flows: this is the case of Flexible Alternating Current Transmission System (FACTS) devices. Additionally, the system will face the challenge of integration of high consumption from data centres, electrolysers and electric vehicle charging stations, which are also interfaced by power electronics. Interactions between the vast number of power electronics have already resulted in converter driven and resonance stability issues. These stability issues cause oscillations within the power system, leading to system instability, in timeframes much shorter (milliseconds compared to seconds) than "conventional" stability challenges.

According to CIGRE [5], the ability of power system equipment to operate in a stable manner and for the system as a whole to recover from major disturbances, is influenced by the electrical "strength" of the system at the point where equipment connects. Intuitively, "stronger" systems are more tolerant to variations and perturbations in system's operating state and recover more easily from major disturbances such as faults and the sudden loss of equipment. Introduction of power electronics has generally reduced the "strength" of the system (in the conventional sense). For new stability phenomena, "weaker" systems experience greater volume and severity of converter-driven instability events.

The latest experiences with operating large power-electronic coupled new renewable parks have demonstrated that forced oscillations injected by these power generation sources can lead to critical power system operation modes. Therefore, there is a need for early detection of those oscillations as well as identification of their source. The current pragmatic approach of immediate disconnection of such sources has shown to be the most efficient response.

Stability assessment procedures are always based on simulation models, which contain models of the grid, simplified as a reduced network with a voltage source and an impedance and the converter itself, also modelled as a voltage or current source with frequency dependent impedance characteristics. The main challenge for future stability assessment processes would be to have an appropriate model of the converter systems, to compute the possible interactions between different converter systems and the electrical network system. The quality of the results of the simulation-based stability analysis is always coupled to the quality of the simulation models, representing the real system components. Concerning this point, the complexity of electromagnetic transient models for the network and the assets (generators, demands, FACTS and HVDCs) is huge and involves deep confidentiality challenges, as the know-how of the controls of each manufacturer's devices is coded in these models.

Minor changes in the grid topology can lead to controller interactions among nearby converters. On the other hand, measurement-based analysis is equally important. It can help identify and thoroughly analyse any instability that might arise or prevent it from occurring in the best case.

3.1.1 Challenges and required mitigation measures

The main challenges are based on the following new configurations [6, 7, 8]:

- Conventional generation and demand (resistive load, synchronous and induction motors) are stepwise replaced by converter-based generation and demand,
- The percentage of cable connections versus overhead lines is increasing,
- HVDC circuits for long-distance interconnections becomes reality,
- FACTS devices are more and more used in the system.

This implies the following consequences:

- System inertia and system strength (traditionally measured by short circuit power) are decreasing,
- Harmonic resonance frequencies are shifted close to the system rated frequency and the amount of HVAC cables in the system can result in related harmonic resonances,
- Power electronics possess very short reaction times and corresponding fast control loops which can be subject of additional harmonic disturbances and/or corresponding controller interactions, SSTI, etc.
- There is a need to get to know the real capabilities of power electronics concerning short circuit ratio and to be able to facilitate the deployment of these devices in such a way that control interaction induced and general instabilities are avoided, by means of establishing certain rules of connection and operation that grant the required level of short circuit power,
- The optimal rating of power electronic interfaced devices should consider headroom for required short circuit ratio or grid forming behaviour, where those devices used to be rated at their optimal economic use case in the past.

Those challenges create new modelling and measurement/monitoring needs as:

- Detailed Electromagnetic Transient (EMT) modelling for the faster control loops and power electronic devices.
- Point-on-wave measurement devices with high reporting and sampling rates and proper time synchronisation.
- Edge computing (or decentralised) devices at the points of measuring, to evaluate the POW measurements and only store the necessary results to be transmitted and stored into the central data stations.
- Continuous Point on Wave (CPoW) data sent to a centralised server using a compression algorithm to drastically limit the communication bandwidth.

As a brief insight into mitigation methods, the following measures are proposed (further elaborated later in the report):

- Coordination, adaption of converter controller parameters.
- Changes in operational scenarios (redispatching and topological changes).
- Addition of damping devices or other power electronic equipment with grid forming capabilities.
- Increase of power system voltage stiffness (system strength) [9].
- The hosting capacity of the network for power electronic interfaced assets (generation, demand, FACTS and HVDC) must consider short circuit ratio needs.

Another important subject related to the challenges of energy transition which needs more attention, is voltage control of the entire power system. Recent events of voltage collapse (for example the South-East Europe incident in 2024) demonstrated that a higher engagement in voltage control from the new renewable generation is required. This means a paradigm change from simply PQ-control in the direction of voltage control with a related coordination including prequalification tests etc.

To ensure good enough coordination and power quality control on the interfaces between TSOs, DSOs and generation companies, there is a need to install well-synchronised point on wave measurement equipment to enable documenting the individual impact and confirm behaviour correspondingly.

3.2 Identified instability detection technologies

Suitable physical devices for measuring different types of instability, along with methods for identifying and mitigating these phenomena, are outlined in Table 1.

Measurement-driven methods are essential for accurately tuning dynamic models and calibration, while simulation-based methods play a key role in determining effective countermeasures.

Instability class		Physical devices	Simulation methods	Monitoring tools
Rotor angle Stability	**Small disturbance (between 0.1 Hz and 0.4 Hz)**	PMUs, DFRs	Modal analysis, Eigenvalue analysis, Damping measurements, Small signal stability Analysis, Power oscillations detectors	Online DSA, WAMS
	Transient stability	PMUs	RMS analyses, Energy criteria (i.e. Lyapunov), Angular displacement tools	Online DSA, WAMS
Voltage Stability	**Small disturbance**	PMUs, WMUs, VDRs, DFRs	Small signal stability analysis	Online DSA, WAMS
	Large disturbance	PMUs	Voltage collapse/increase algorithms, RMS simulations	Online DSA, WAMS
Frequency Stability	**Short-term**	PMUs, DFRs, FDRs	RMS simulations	Online DSA, WAMS
	Long-term	PMUs	RMS simulations, One-busbar approaches	WAMS
Resonance Stability	**Electrical**	PMUs, DFRs, High sampling rate PMUs, WMUs	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 PMUs, DFRs, WMUs	EMT simulations	Online torsional resonance monitoring
Converter-driven Stability	**Slow interaction (<10 Hz)**	PMUs, WMUs, DFRs	Modal Analysis, Eigenvalue analysis, Small signal stability analysis, Dynamic response analysis	WAMS, Online DSA, Advanced WAMS monitoring
	Fast interaction (10 Hz to 100 Hz or higher)	High sampling rate PMUs, DFR, WMUs	Modal Analysis, Eigenvalue analysis, Small signal stability analysis, Impedance based analysis tools	Advanced WAMS monitoring

Table 1: Measurement-based instability detection technologies per stability phenomena

3.3 Instability Detection Technologies Parameters

To better understand the limitations of the technologies previously listed, Table 2 lists key parameters that influence different physical devices.

Technology	Reporting rate	Communication delay	Measurement time synchronisation	Type of measurements
Phasor Measurement unit (PMU)	5–100 ms	<100 ms to seconds	Yes	Voltage and Current Phasor (amplitude and phase), P, Q, f and df/dt
Digital Fault Recorder (DFR)	Data send after the event	–	No, but can be	Voltage and Current point on wave (sampling from 1 to hundreds of kHz)
Synchronised Point on Wave (POW)	< 5 ms [10]	–	Yes	Voltage and Current point on wave (sampling from 200 Hz to tens of kHz)
Remote Terminal Unit (RTU)	1–10 s	<1 second	No	RMS
Power Quality (PQ) meter	200 ms-minutes	100 ms – 1 s	Yes (at least for some TSOs) [11]	Voltage and Current waveform and RMS, P, Q, f, df/dt, harmonics, flickers, imbalance (Often only averaged values of these are measured)

Table 2: Monitoring tools and their characteristic parameters

As Table 2 shows, beyond PMUs, WMUs are already used for measurements with much higher sam-pling rate. A significant difference between WMU and PMU devices is that WMU devices sample and report measurements at a higher rate than PMU devices, even up to a million samples/s. PMU data is also filtered and processed to obtain the synchrophasors, but WMU measurements are sequential, time-stamped scalar measures of a current or voltage with minimal filtering. This also means that from WMU measurements synchrophasors can also be calculated. Figure 2 depicts the capability of PMU and WMU devices with respect to fast transients. During transient events the waveform is not sinusoidal, and PMUs don't handle these well.

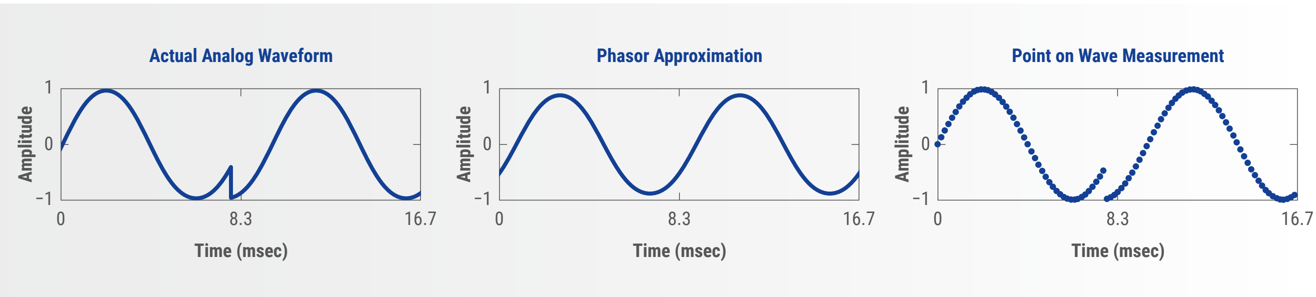


Figure 2: Comparison of PMU and WMU results for a fast transient [6]

3.4 Determining Mitigation Actions

Actions to mitigate instability stemming from oscillations require further classification to provide clarity as depending on the type of oscillation: natural or forced oscillations, different mitigation actions can be realised. Forced oscillations stem from faulty equipment or incompatible control systems and require real time detection and correction. Natural oscillations, however, stem from a combination of many elements within the power system that collectively produce poor damping. In such cases, constant monitoring and post incident analysis is better suited. In systems that have poor damping, real-time mitigation, pre-operation analysis and planning is also important.

3.4.1 Preventive and corrective actions of different phenomena

In line with reference to the phenomena classification introduced in the previous chapter, it is possible to divide the actions to contrast instability into two families:

- Preventive actions, aimed to prevent the instability
- Corrective actions, manually or automatically activated, to mitigate or avoid the instability

Both preventive and corrective actions can be further subdivided based on the moment in time at which they are implemented from long-term actions to real-time actions. Table 3 condenses preventive and corrective actions per stability phenomena.

Preventive Actions

Preventive actions are related to identifying instability phenomena ahead of their occurrence and are more related to the overall system design.

Starting from long-term preventive actions, a crucial role is covered by the planning and developing of new grid intervention like the installation of synchronous condensers, static synchronous compensators (STATCOMs), or either, the adoption of series compensated lines to improve stability margins.

Medium-term actions include all those aimed at the development of preventive systems. By preventive systems, we mean the development of automatic systems like defence system, protections, under voltage load shedding (UVLS), under frequency load shedding (UFLS), all of which plays a key role in the system design to improve system stability. The development of preventive systems is not the only one action which can be taken to avoid instability. Others can be the development of innovative market services with the purpose to enable battery energy storage system (BESS) systems to provide regulation services.

Moving closely to the real time, the use of offline tools can be included to choose preventive actions. Offline tools can be used to perform grid studies, both long and short term, data analysis tools, recordings etc. in order to identify instability phenomena and propose mitigation actions such as topological changes, cancelled maintenance, must-run units, redispatching and countertrading.

Preventive actions in real-time involve all the tools to ensure the stability of the electrical national grid facing the instability phenomena in real time or quasi real-time timeframes. The adoption of measurement-driven or analytic tools to identify relevant preventive action can be observed in preventive manoeuvres, for example, operated by the control room. Also, the availability of Human-Machine Interface (HMI) features and facilities in the control room for real-time operations plays a key role in the mitigation of instability phenomena.

Corrective Actions

Corrective actions, instead, are considered when instability occurs or following its occurrence. They are more related to operational system management and can be divided into automatic and manual corrective actions.

Automatic actions are all those actions which, in real-time, provide a corrective action without the human intervention. Those are, for example, the intervention of the Defence System and of protections. Clearly, to operate in a resolutive manner, they must be properly designed. In fact, these systems are both part of the corrective actions in terms of operational system management, and a part of the preventive actions related to system design.

In opposition to the automatic actions previously described, the manual actions are all the ones acted by the control room to avoid instability. These can be, for example, the redispatching or operational manoeuvres, such as changes in the grid configuration. Control room requires also HMI facilities and real-time tools to monitor instability phenomena prior to and following the application of corrective actions.

Countermeasures

Both preventive and corrective actions involve countermeasures that must be properly designed starting from the long-term planning stage according to coordination, reliability and effectiveness criteria. Once these countermeasures are implemented, a crucial aspect is the ability to make their effects fully observable and controllable for assessing their actual effectiveness in mitigating instability phenomena.

To validate these design requirements, PMU-based fault recordings for post-disturbance analysis and Site Acceptance Tests (SATs) for damping verification are essential. Based on the instability classification introduced in Chapter 3, countermeasures can be categorised according to the instability phenomena they aim to control and mitigate.

Instability Class	Preventive actions (system design and planning)	Corrective actions (real-time operations management)
Rotor angle stability	› Installation of synchronous condensers with high-inertia flywheels › IBR P/Q POD for active/reactive power damping	› Wide Area Monitoring and Protection (WAMPAC) › Advanced defense logics › Redispatching actions
Voltage stability	› Installation of STATCOMs (fast reactive power management) and synchronous condensers › IBR Q POD for reactive power damping › Improving grid-forming control leading to a mature and resilient technology	› Wide Area Monitoring and Protection (WAMPAC) › Advanced defense logics
Frequency stability	› Installation of high-inertia flywheels in synchronous condensers › Improving grid-forming technology with inverter-based storage systems	› Wide Area Monitoring and Protection (WAMPAC) › Advanced defense logics
Converter-driven stability	› Improving grid-forming control for inverter-based storage and renewables leading to a mature and resilient technology	› Wide Area Monitoring and Protection (WAMPAC) › Power quality devices to monitor IBR based harmonics and subharmonics
Resonance stability	› Active and passive filters on IBR resources connected to the system	› Power quality devices or WMUs for monitoring

Table 3: Preventive and corrective actions for different stability phenomena

4 Measurement-Based Instability Detection Technologies

This chapter narrows the scope of instability detection technologies to measurement-based devices. The motivation to do so stems from the importance of WAMS role in monitoring and managing growing dynamics of stability phenomena within the European electricity transmission system. Measurement based devices (such as PMUs, DFRs and WMU measurement units) are key components within WAMS, and narrowing the scope of this paper allows for deeper insights and tailored research needs and recommendations.

4.1 Quality of Measurements and Estimates

Measurements are influenced by noise and errors introduced throughout the whole measurement chain. This includes current and voltage transformers, the analogue-to-digital conversion in the measurement device, and any data processing and filtering performed after sampling. Sampling and data processing also introduce latency (lag) between the moment an event occurs and the moment it is reported by the device. Point-on-wave measurements are samples of the voltage and current waveforms with minimal processing. Other quantities, such as frequency and Rate of Change of Frequency (RoCoF), cannot be measured directly and must be estimated from the measured waveforms. Phasors reported by PMUs are also estimates rather than measurements, while often referred to as measurements when the distinction is not important.

Estimates are based on a window of samples of the voltage and current waveforms. This means that they are not only affected by the methods of measurement used, but also by the methods of estimation. Since the sampled signals are never stationary, the reported quantities are averages over the chosen time window. The length of this time window affects the estimates' sensitivity to noise and their fidelity during dynamic changes in the signal. Errors in the phase angle estimate are amplified in the frequency and RoCoF estimates since these are derivatives of the phase angle.

The quality of such estimates depends on which method of numerical differentiation is used. There is always a trade-off between noise level, time alignment and reporting latency. The quality of measurements and estimates are crucial to functioning and validity of measurement-based instability detection technologies.

Specifications for PMU measurements can be found in the standard IEC/IEEE 60255-118-1 Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems – Measurements [12]. The standard divides PMUs into two classes, the measurement (M) and protection (P) classes, where the latter has lower latency but allows more noise.

The chosen data format can greatly affect the quality of measurements received from PMUs. According to the IEEE Std C37.118.2-2024 - IEEE Standard for Synchrophasor Data Transfer for Power Systems [13], measurements may be transferred in a 16-bit integer format or a 32-bit floating point format. This is specified in the FORMAT field of the PMU configuration frame, and both options are valid for configuration frames 1 through 3, where configuration frame 3 is the most recent transfer standard. The integer format gives significantly lower resolution than the floating-point format. This is especially problematic in the case of frequency measurements, where the resolution in the integer number format is 1 mHz, which introduces noise in the data in the same order of magnitude as ambient power system oscillations, making such phenomena difficult to monitor. The integer format allows more compressed data storage, but due to its limitations it should be considered obsolete, and all PMUs should be set to transferring in the floating-point data format if possible.

4.2 Limitations of Current Measurement-Based Instability Detection Technologies

4.2.1 Sampling Frequencies and Reporting Rates

The range of instability phenomena which can be observed depends on the resolution of the data.

The theoretical limit is the Nyquist frequency (half of the time resolution of the data), but in practice the upper limit will be somewhat lower than this.

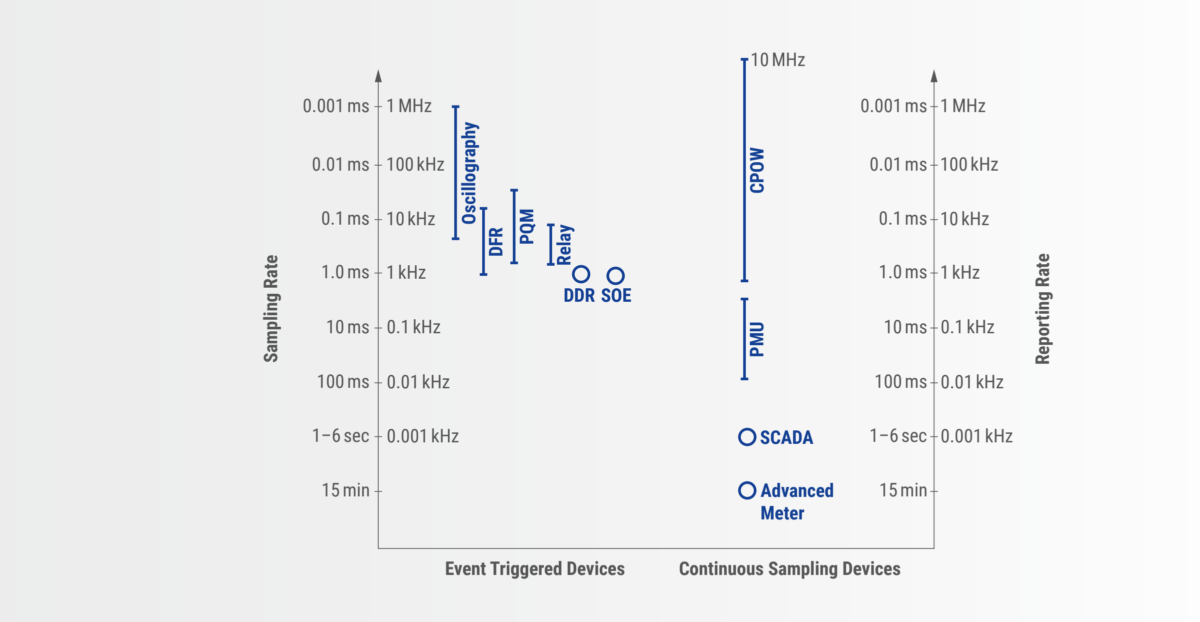


Figure 3: Grid monitoring devices by resolution and data continuity. This graphic uses "sampling rate" for event-triggered devices be-cause they don't report; the user pulls the sampled data to analyse it as collected. Continuous sampling devices report out at a user selected rate which may be slower than its sampling rate [6]

The resolution of the data received from the measurement device depends on the type of the device. It is important to distinguish between the rate at which the device samples voltages and currents, and the rate at which it reports its measurements or estimates (see Figure 3):

The sampling frequency or sampling rate refers to the frequency at which the device, using an analogue-to-digital converter (ADC), samples input current and voltage waveforms. It is typically expressed in Hertz (Hz) rather than in frames per second. In power systems with a nominal frequency of 50 Hz, PMU sampling frequencies are often carried depending on device manufacturer, typically 64 – 320 samples per cycle or 3.2 – 16 kHz.

The reporting rate indicates how often the device reports its measurements. The reporting rate is set by the user and is usually expressed in samples or frames per second (fps). This is significantly lower than the sampling rate of the PMU.

For point-on-wave devices, the reporting rate may be the same as the sampling frequency. In any case, the reporting rate dictates the resolution of the data reported by the measurement device, which from the perspective of the receiving end will be the sampling frequency of the *data*. Hence the reporting rate of the device is the parameter that limits the frequency range of observable phenomena in the data.

With the changing power system, new and evolving stability phenomena are moving increasingly towards shorter timeframes. The current sampling and reporting rate cannot keep up with the shorter timeframes to be able to detect and employ required corrective measures to ensure grid stability. Transitioning to higher sampling and reporting rates still pose challenges in terms of the wider devices along the measurement chain and their capacity. There is a possibility of signal attenuation along the measurement chain when stepping up to higher sampling and reporting rates.

4.2.2 Sensor Bandwidths

When CPoW is used to measure high frequency phenomena the limitation of classical sensors (TP, TI) can be hit in terms of bandwidth. It should be underlined that there may be a need to use adapted sensors to capture higher frequency phenomena.

Sensors have limited bandwidths. In IEC Technical Report 61869-103 [14] some ranges of measurement frequencies where the devices can be used are given. For current transformer technologies see Figure 4:

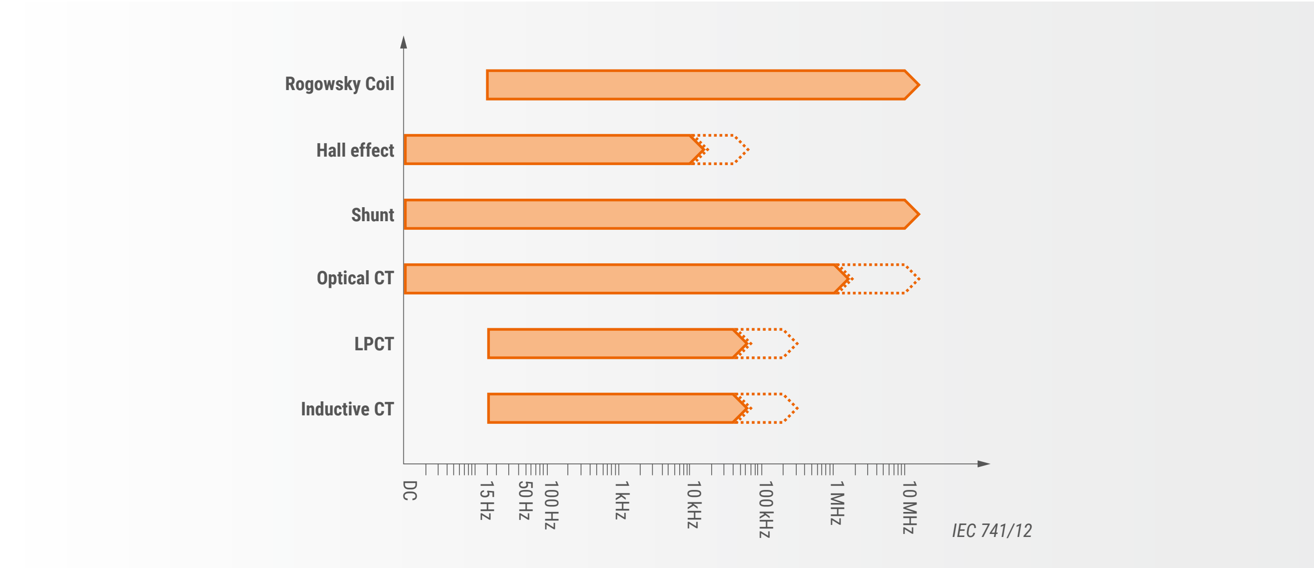


Figure 4: Bandwidth limitations for Current Transformers

For voltage transformer technologies see Figure 5:

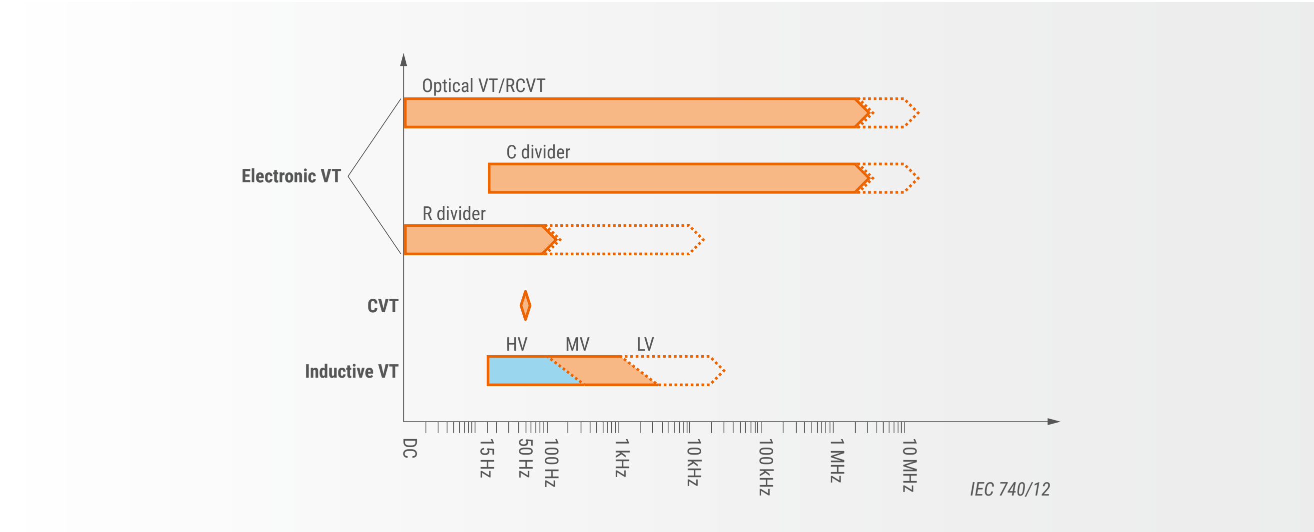


Figure 5: Bandwidth limitations for Voltage Transformers

It is noticed that the problem of bandwidth is obvious for the most commonly used voltage transformers, capacitive voltage transformer (CVT) and inductive voltage transformer (IVT in the graph). To accurately monitor the fast transient and harmonics and potentially low frequencies, some corrections need to be applied to the measurement.

For CVTs, there are compensation devices that are able correct the measurement in real time and enables the CVT to perform harmonics measurements [15].

4.2.3 Data Collection and Recording

Data collection, recording and storage are among the main challenges in utilising measurement recording devices depending on their data acquisition sampling frequency, reporting rate and waveform sampling technique described above. To clarify these challenges the terminology used in this document is as follows: PMUs continuously stream synchronised measurement data to a dedicated PDC for aggregation and analysis. The benefits of PMU measurements are already well established, and the advancement of this technology enabled monitoring of electromechanical phenomena that were previously unobservable. PMUs use phasor representation of a sinusoid to describe the input signal which limits their effectiveness in detecting faults and transient events where the signal waveform deviates from a sinusoidal shape. During dynamic events the magnitude and phase can change abruptly and rapidly. Similarly, the increasing use of inverter-based technology introduces new stability challenges, such as electromagnetic transients, which require different measurement techniques and higher reporting rates – capabilities that are not inherent to PMUs.

For this purpose, high resolution devices with a reporting rate >200 samples/second are required to capture the waveform more accurately. Some of these devices have been available in system operation for years, but they are not intended for monitoring instability in the system. For example, DFR or Power Quality (PQ) devices deliver measurements with a much higher resolution, but in general the recording time of disturbances is very limited, and (if not already inbuilt) proper synchronisation have to be applied. Recording is generally triggered by events detected by the DFR based on its input signals or digital signals activated through protection equipment.

For synchrophasor based applications, low latency, ideally kept under 100 ms (from PMU to control centre) is essential to allow the data to be processed in real time. Since PMUs produce large volumes of data (10 to 200 samples per second and per PMU unit) high communication bandwidth is essential to handle these volumes of data (standard bandwidth under IEEE C37.118.2-2011 is 100 reports per second). Most commonly used communication infrastructure includes fibre optic network and ethernet and IP based networks.

The primary protocol for exchanging synchrophasor data is IEEE C37.118, which was originally developed for transmitting data from PMUs to control centres. This protocol consists of two parts:

- Part 1 defines synchrophasor, frequency, and RoCoF measurements. It also establishes evaluation methods and compliance requirements under both static and dynamic conditions.
- Part 2 focuses on message structure, detailing types, usage, content, and data formats for real-time communication between PMUs, PDCs and other related applications.

In 2024, IEEE introduced IEEE 2664-2024, the Streaming Telemetry Transport Protocol (STTP), designed for efficiently handling large-scale, continuous streaming data. STTP is a publish-subscribe protocol that integrates TLS encryption for secure authentication and asymmetric encryption for User Datagram Protocol (UDP) communication. It enhances scalability through data compression to reduce bandwidth consumption and optimises packet size to minimise fragmentation and speed up Transmission Control Protocol (TCP) transmission while reducing UDP packet loss.

While IEEE C37.118 was developed primarily for substation-to-control centre data exchange, its frame-based structure – where frame size depends on the number of measurement points – is not optimised for large-scale data transmission. It also lacks built-in encryption for secure communication.

For future synchrophasor applications, STTP presents a more efficient solution. It supports high-frequency data sampling, optimises Maximum Transmission Unit (MTU) packet sizes for improved network efficiency, reduces losses by minimising frame-size stress on networks, and simplifies configuration management through metadata exchange. Additionally, its support for encrypted data transfer ensures secure communications, making it a strong candidate for evolving synchrophasor systems. Nevertheless, the success of this protocol will strongly depend on its implementation from the device vendors that is not yet wide at the moment of writing of the present paper.

5 Research Needs and Recommendations

5.1 Strategies for Data Transfer, Handling, Storage and architecture for WMUs

As introduced in the previous section, measurement devices allowing high frequency sampling and reporting rates are already available. They are mainly used to assess system faults (DFR) or power quality (PQM), not continuously transferring data to a centralised system. In addition, they are mostly used to perform Automatic Fault Analysis and assessment of harmonic compatibility, the used analysis functions are not specialised to assess system stability.

The availability of WMUs (with or without continuous streaming functionalities) opens a lot of possibilities but it comes with several still to be faced open questions. More specifically in the following areas:

- Choice between continuous streaming or "on trigger" data exchange. And relatively how to define the triggers that can allow detection and analysis of super- and sub-synchronous events in the system.
- Efficient handling of data, minimisation of the needed communication bandwidth and storage needs, using for example compression algorithms. A trade-off between central and local data processing has to be found.
- Choice on the architecture centralised vs. decentralised "edge" analysis. In the first architecture all the data is sent to a central server where the analysis is performed while in the second the computation is performed close to the measurement units. The former has the advantage that comparison and relation between different measurement units can be performed with the disadvantage of needing high bandwidth for long-distance data exchange. The latter has the advantage of reducing the communication bandwidth on long distances needs but has the disadvantage that it is not possible to perform comparison between different measurement far from each other.

Relevant Stakeholders

Academia | Manufacturers | TSO

5.2 Standardisation of data exchange

While there are some standards with respect to PMUs and WMUs as cited by IEEE (IEEE C37.118.1), there is still a need for standardisation of the outputs and calculations from these measurement-based instability detection technologies. There are several efforts already in place in ENTSO-E, particularly the Common Information Model (CIM) Working Group, liaising with relevant IEC working groups to ensure standards are developed with TSO requirements. Measurement, including PMU, and the result of State Estimator and Power flow are already included in the Common Grid Model Exchange Standard (CGMES) 3.0 (corresponding with IEC 61970-600-1 and 61970-600-2). CGMES also include reference to Common Information Model (CIM) for Dynamics (transient stability analysis). However, the more recent Dynamics (DY) profile in the IEC 61970 family of standards (refer to the IEC 61970-302:2024 and the IEC 61970-457:2024) includes the latest description to handle stability and voltage control including inertia studies. Similarly, fault handling and System Integrity Protection Scheme are also very relevant for WAMS System. These topics have been addressed in the CGMES extension known as Network Code Profiles (NCP) for Regional Coordination Processes (RCP) available on the ENTSO-E CGMES Library website. IEC plans to include better support for PMU and WAMS control and supervision in the next version of the CGMES standard (e.g. v3.1). TSOs and relevant actors exchange are welcomed to write relevant requirement, so ENTSO-E conveys them in upcoming version of IEC standards such as CGMES. Coupled with this, continued collaboration is required to better data exchange and their standards and frameworks.

Current vendors use different techniques to assess system instability and often these are proprietary and their implementation details not available to the user.The outputs of these instability detection devices are not homogeneous and cannot in general be compared. CIM family of standards addresses this issue by structuring information with a vendor-agnostic approach, ENTSO-E supports its members in implementing standards for calculation software (not device-oriented standards) and expanding them. This paper recommends TSOs to contact the ENTSO-E CIM WG to write further requirements for data exchanges and collaborate with relevant software vendors. Continued collaboration and research efforts to identify future data requirements alongside relevant stakeholders are crucial to forwarding stability management efforts.

Relevant Stakeholders

Academia | Manufacturers | DSO | TSO | Standardisation bodies

5.3 Evaluation of new stability phenomena and interactions with measurement-based devices

There is a need to coordinate on research regarding new stability phenomena arising due to an evolving grid. The increased concentration of IBRs is leading to increasing observations of converter driven and resonance instability phenomena.

These new high frequency phenomena require research and innovation for the development of algorithms for detection, analysis and subsequent visualisation that present measurement-based devices and analysis algorithms cannot tackle sufficiently. In addition, mitigation measures for the observed phenomena shall be researched.

Relevant Stakeholders

Academia | Manufacturers | DSO | TSO

5.4 Online wide area oscillations detection algorithms development

The development of new algorithms is essential for effective instability detection. Modal properties of the main oscillatory modes can be evaluated in real time through processing systems based on advanced algorithms, such as Dynamic Mode Decomposition (DMD), for example.

Thanks to the availability of PMUs and WMUs installed in the field, it is possible to develop an Online Wide-Area Oscillation Detection System. More in general, data-driven modal identification technique processes the frequency measurements provided by the measurement devices (e.g. PMUs and WMUs) and performs modal analysis to identify the main oscillatory modes that characterise the system's dynamic behavior. Moreover, data-driven modal identification algorithms can dynamically detect the effective number of oscillatory modes present within a given time window.

The development of such algorithms is crucial for the continuous improvement of instability detection techniques. The availability of wide area measurements with higher sampling, combined with the application of algorithms based on the modal identification technique, could enable TSOs to monitor and identify phenomena that are not yet observable with current real-time monitoring systems.

Relevant Stakeholders

Academia | Manufacturers | TSO

5.5 Approach for algorithms handling real time analysis

Moving forward, the analysis of grid stability increasingly needs to be tackled at a real time scope (very low time delay). Some listed approaches require further research and development to realise use in future grids, tackling both evolving phenomena as well as newly identified ones.

- Robust (linear/hybrid) state estimator
- Modal analysis (measurement, not simulation)
- Forced oscillations detection and localisation of the source based on measurements
- Assessment of sub- and super-synchronous phenomena

Relevant Stakeholders

Academia | Manufacturers | TSO

5.6 Time synchronisation

Synchronisation of time stamps for data from the measurement-based devices relying mostly on GPS signals which have several limitations. While alternatives exist, based on highly precise atomic clocks provided over the network, research, which considers cost and ease of deployment as well as cyber-security factors, is needed.

Relevant Stakeholders

Academia | Manufacturers | TSO

5.7 Offshore and WAMS implementation standardisation

With growing offshore networks, influence of these offshore wind connections to the grid are evaluated using PMUs. Large scale offshore renewable generation means additional research and solutions are needed to estimate provisional inertia and establish on-line monitoring for the different onshore synchronous areas. New emerging technologies and systems will help manage frequency stability better in the future, e.g., WAMS. The specific challenges of measuring all stability phenomena in the offshore network would benefit from standardisation in implementation.

Relevant Stakeholders

Manufacturers | TSO | Standardisation bodies

5.8 Future approaches to data handling

Data volumes are vast and increasingly various; the large volumes of data consist of widely different types of data. Selecting an appropriate database handling approach is required. This must also address the issues of availability of historical data. A consensus on best practices regarding how long historical data should be stored will provide better harmonisation of such data handling frameworks.

Evolving technologies must also be employed to better handle data; recognising and deploying relevant AI applications will be crucial to future operations.

The potential applicability of distributed learning and edge computing also presents promising solutions that require further research study. These technologies offer significant advantages in terms of scalability, efficiency, and real-time data processing. By leveraging distributed learning, computational tasks can be shared across multiple nodes, enhancing processing speed and resource optimisation. Edge computing, on the other hand, enables local data analysis, reducing latency and bandwidth usage while ensuring timely responses. Together, these approaches have great potential to revolutionise the handling of large datasets, providing critical insights and actionable information to control centres.

Relevant Stakeholders

Academia | Manufacturers | DSO | TSO

6 Conclusion

The evolving power system needs grid stability measures that keep up with it. This technical report highlights the needs for measurement-based instability detection technologies by evaluating the limitations currently faced by measurement-based technologies and the research and innovation needs recognised by TSOs to tackle them. The focus on measurement-based technologies is a conscious effort by TSOs to build a tighter scope for evaluation and subsequent highlighting of research and innovation needs.

The limitations can be placed under the following categories:

- Sampling frequencies and reporting rates of measurement-based technologies being short of keeping up with instability events that occur in increasingly shorter timeframes.
- Sensor bandwidths that are not able to cover all ranges of instability events.
- Data collections and recording difficulties in terms of both volumes of data and speed of processing instability events.
- Availability of algorithm and post-processing functionalities able to detect instability and their relative sources.

As an ENTSO-E output, the collective perspective of TSOs in tackling these limitations are along multiple axes, covering the needs for further understanding and research along existing technologies and developing new approaches in terms of technology deployment. The needs for research and innovation are highlighted under the following directions with relevance to various stakeholders in Table 4.

The evaluation of these avenues has also highlighted the relevant stakeholders that can play a significant role in furthering grid stability through measurement-based detection technologies. The report identifies certain actions for ENTSO-E in the short- and medium-term in Table 5.

Relevance Matrix	Academia	Manufacturers	DSO	TSO	Standardisation Bodies
Standardisation of Data Exchange	*	***	***	***	***
Evaluation of new stability phenomena and interactions with measurement-based devices	***	**	***	***	**
Online wide area oscillations detection algorithms development	**	***	**	***	*
Approach for algorithms handling real time analysis	**	***	***	***	**
Time synchronisation	*	***	**	***	*
Offshore and WAMS implementation standardisation	*	***	**	***	***
Future approaches to data handling	***	***	***	***	***

Table 4: Relevance Matrix for identified research actions for various stakeholders: * Monitor and receive updates, ** Informed and Consulted, *** Informed and Collaborative.

Timeframe	Actions
Short (<1 year)	› Identify future areas of research and innovation in stability management. › Clarify power system stability challenges for the wider audiences. › Update ENTSO-E Position Paper on stability management in PEID systems.
Medium (2–3 years)	› Further explore WAMS implementation, data handling approaches, and standardisation work under WG CIM. › Continue to facilitate knowledge sharing among TSOs, workshops and dedicated spaces for knowledge sharing.

Table 5: Short- and medium-term actions on stability management for ENTSO-E

Glossary

ADC	analogue-to-digital converter
BESS	Battery Energy Storage System
CIM	Common Information Model
CPoW	Continuous Point on Wave
CVT	Capacitive Voltage Transformer
DMD	Dynamic Mode Decomposition
DFR	Digital Fault Recorder
DY	Dynamics
ENTSO-E	European Network of Transmission System Operators for Electricity
EMT	Electromagnetic Transient
FACTS	Flexible Alternating Current Transmission System
fps	frames per second
HMI	Human Machine Interface
HZ	Hertz
M	Measurement
MTU	Maximum Transmission Unit
NCP	Network Code Profiles
P	Protection
PCG	Policy and Communication Group
PEIDs	Power Electronics Interfaced Devices
PID	Project Initiation Document
POW	Point on Wave
PMU	Phasor Measurement Unit
PQ	Power Quality
RCP	Regional Coordination Processes
RDIC	Research Development and Innovation Committee
RoCoF	Rate of Change of Frequency
SOC	System Operations Committee
SDC	System Development Committee
STTP	Streaming Telemetry Transport Protocol
TR	Transient Recorder
TSO	Transmission System Operator
UDP	User Datagram Protocol
UVLS	Under Voltage Load Shedding
WAMS	Wide Area Measurement System
WAMPAC	Wide Area Monitoring and Protection
WMU	Waveform Measurement Units

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