Position Paper on System Stability and Inertia

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Content

1. Executive summary

This document presents the position of GO15 members on the main challenges and the most promising enabling solutions to enhance the stability of low inertia and power converters-dominated power transmission systems. It introduces a comprehensive classification of the main phenomena influencing power system stability, examining research directions and promising technologies and methodologies for improving dynamic grid performance in the presence of large-scale adoption of distributed power converter-based generators.

The concept of power system stability is re-examined, taking into account the potential effects arising from the large-scale replacement of conventional synchronous generators by distributed generation systems based on renewable energy sources. Particular attention is paid to critical issues facing modern power systems, including decreasing inertia and vulnerability to dynamic disturbances on multiple time scales, and their potential impacts on the stability, flexibility, and resilience of power systems. The paper includes a detailed analysis of the most promising enabling technologies for improving system stability.

Moreover, the document summarizes and discusses the results of surveys submitted to GO15 members on power system inertia and stability, presenting best practices and providing valuable insights.

Finally, the document makes few recommendations at three levels: policy and planning, regulatory and technical. The significant penetration of converter interface generators (CIGs) requires substantial revisions to conventional policies governing the planning, operation and regulation of power systems [65]. Several countries have witnessed the negative effects of the rapid growth of CIGs connected to the grid, underlining the importance of defining and implementing corrective actions to improve grid flexibility and mitigate the impact on power system stability and security.

2. Scope

The scope of this paper is to provide the position of GO15 members on the main challenges and the most promising enabling solutions to enhance the stability of low inertia and power converters-dominated power transmission systems. In this context, it analyzes the main phenomena affecting the secure and reliable operation of future transmission networks, which poses significant challenges to power system operators all around the world, such as the replacement of large synchronous generators with distributed power converter-based generating units, the massive penetration of renewable power generators, and the increasing system interconnections. The enabling technologies and methodologies applied by the GO15 members for addressing these challenging issues are analyzed in detail, and the results of two surveys submitted to the GO15 members on power system Inertia and Stability are presented and discussed in the task of presenting best practices and providing valuable insights.

3. Introduction

As the global energy landscape undergoes a transformative transition towards sustainability and decarbonization, the role of Transmission System Operators (TSOs) becomes increasingly pivotal in ensuring the stability and reliability of power systems, balancing resource adequacy, economics, and environmental concerns. Indeed, electrical power transmission systems face numerous challenges, such as replacing conventional large synchronous generators with inverter-based distributed generating units, enhancing the transfer capability to enable multiple energy transactions, dispatching massive, dispersed energy resources, managing the dichotomy between grid ownership versus system operation, and ensuring reliability coordination. Additionally, the operational environment of modern transmission grids is becoming more demanding because of the constantly evolving functions of a power system, which is transitioning from operation jurisdiction to control responsibility while meeting the rising demand for reliability.

In this new scenario, ensuring the secure and reliable operation of power transmission systems is becoming increasingly challenging due to the rising level of system uncertainties and complex perturbation phenomena, which are mainly due to:

- the rising number of network interconnections.
- the increasing components loading, which saturates the available transfer capability.
- the massive pervasion of geographically dispersed generators equipped with inverter-based grid interfaces.
- the dramatic reduction of grid flexibility due to the replacement of large programmable generation units with small and dispersed renewable power generators.
- the larger number of power transactions, which are driven by complex market dynamics.
- the need for a more detailed dynamic security assessment analysis aimed at analyzing the impacts of multiple contingencies (i.e. N-2 security criteria).
- the severe grid perturbations induced by the large-scale deployment of renewable power generators mainly depend on the highly variable power injections and voltage dynamics.

The increasing prevalence of these complex phenomena in power transmission system operation raises significant concerns about the grid vulnerability to dynamic perturbations, highlighting the urgent need for identifying robust and resilient strategies to enhance **power system stability**, which is a cornerstone of energy infrastructure defined as "**the ability of the system, for a given initial**

operating condition, to return to a state of operating equilibrium after a physical disturbance, with most of the variables of the system constrained so that the entire system remains intact".

The ability of a power system to withstand both minor and major dynamic perturbations is crucial for guaranteeing its secure and reliable operation and encompasses various aspects such as frequency control, voltage regulation, and overall resilience against disturbances. While minor disturbances such as load variations are relatively easier to handle, major disturbances like generator failures or critical high voltage transmission line faults induce sensible grid perturbations with severe effects on the stability of the transmission system. For this purpose, it is important to develop detailed system security analyses aimed at promptly detecting the potential perturbation phenomena that can affect the system stability and identifying reliable measures for mitigating their impacts. In performing this challenging task, TSOs are asked to manage complex issues that demand innovative solutions and strategic planning.

In particular, the surge in renewable power generators, which generated intermittent and non-programmable power profiles, affects significantly power system stability assessment. Indeed, the integration of these distributed generating units requires the enhancement of the grid operation tools and the decision support systems, which should be able to promptly support TSOs in maintaining system stability despite fluctuations in power generation.

The transition from a centralized to a decentralized power generation paradigm, which is causing a massive deployment of dispersed energy resources, such as distributed generation, energy storage, and demand response, requires enhancing the monitoring technologies and adds further complexities to power system stability analysis, which mainly derives from the bidirectional power flows from the distribution network, the random bus voltage magnitude perturbations, and the need for coordinating multiple and heterogenous energy assets to uphold system stability.

The shift toward decentralized generation is also driving replacing large synchronous generators with distributed units connected to power transmission systems via power electronic interfaces. These converter-interfaced generators perturb grid operation, especially those fueled by non-programmable energy sources (e.g., wind and solar generators), affecting the system stability and reducing system inertia. Inertia is defined as the ability of a system to oppose frequency change as a result of an imbalance between the power produced and the power required. At a low value of inertia the system may not be able to cope with a contingency resulting in worsening stability conditions. For this purpose, TSOs are compelled to integrate new tools for online inertia estimation and decision support into their control centers to maintain frequency stability, especially during sudden disturbances or contingencies, considering that available switched-on generators are changing hour-to-hour. The critical role played by these enhanced grid operation tools is still more relevant as national energy markets become more interconnected, requiring TSOs to face challenges related to cross-border energy exchange, regulatory disparities, and harmonizing operational practices and rules to ensure seamless and secure power flow across borders.

Despite all these perturbing phenomena driven by the decentralized transition process, many power systems globally grapple with aging infrastructure. Hence, TSOs are tasked with upgrading and retrofitting existing transmission assets to enable modern technologies and regulation systems, improve frequency and voltage response, enhance resilience, and extend the lifespan of critical components.

The need to enhance transmission asset management has stimulated the infusion of cutting-edge Information and Communication Technologies (ICTs), such as smart management tools, digital sensors, and pervasive computing systems, which demands a paradigm shift in power system operation. While these digital innovations offer enhanced monitoring and control capabilities, they also necessitate robust cybersecurity measures and seamless integration into existing system operation tools.

The paradigm shift toward cutting-edge ICTs will enable designing protection and control functions that evolve from event-based to model-based approaches, hence allowing congestion management and frequency and voltage control tools to be operable in real time.

This process requires enhancing the transmission planning strategies, which should:

- estimate the mix of generation in mid-term and long-term planning in frames of development plan preparation.
- develop a dynamic study in long-term development aimed at estimating the potential impacts of grid-forming converters and fast frequency storage systems.
- identify proper strategies aimed at ensuring proper level of power system inertia in mid-term and long-term planning studies.

Power transmission planning should also be harmonized with the electricity market structures and regulatory frameworks since they introduce strong uncertainties in TSO decision-making processes. Indeed, adapting to dynamic market conditions while ensuring fair competition and grid reliability requires careful consideration and strategic planning.

In navigating these challenges, TSOs play a central role in fostering a reliable and resilient energy infrastructure that can support the transition to a sustainable and low-carbon future. This necessitates proactive strategies, collaboration with diverse stakeholders, and continuous innovation to uphold system stability in the face of a rapidly changing energy landscape.

4. Definitions

4.1. General definitions

The table 1 defines the main concepts relating to stability and inertia.

Table 1 – definition of concepts relating to stability and inertia

Particulars	Definition
Alert State	Means the state in which the operational parameters of the power system are within their respective operational limits, but a single n-1 contingency leads to violation of system security.
Ancillary Services	In relation to power system operation, means the services necessary to support the grid operation in maintaining power quality, reliability and security of the grid and includes Primary Reserve Ancillary Service, Secondary Reserve Ancillary Service, Tertiary Reserve Ancillary. Service, active power support for load following, reactive power support, black start and such other services
Demand	Means the demand of active power in MW and reactive power in MVAr.
Demand Response	Means variation in electricity usage by the end consumers or by a control area manually or automatically, on standalone or aggregated basis, in response to the system requirements.
Energy Storage System or 'ESS'	In relation to the electricity system, means a facility where electrical energy is converted into any form of energy which can be stored, and subsequently reconverted into electrical energy and injected back into the grid.
Event	Means an unscheduled or unplanned occurrence in the grid including faults, incidents, and breakdowns.
Free Governor Mode of Operation	Means the mode of operation of governor where machines are loaded or unloaded directly in response to grid frequency i.e machine unloads when grid frequency is more than 50 (60)Hz and loads when grid frequency is less than 50 (60) Hz.
Frequency Response Characteristics or FRC	Means automatic, sustained change in the power consumption by load or output of the generators that occurs immediately after a change in the load-generation balance of a control area and which is in a direction to oppose any change in frequency. Mathematically it is equivalent to FRC = Change in Power (ΔP) / Change in Frequency (Δf).
Frequency Response Obligation or FRO	Means the minimum frequency response a control area has to provide in the event of any frequency deviation.

Frequency Response Performance or FRP	Means the ratio of actual frequency response with frequency response obligation.
Frequency Stability	Means the ability of the transmission system to maintain stable frequency in the normal state and after being subjected to a disturbance.
Governor Droop	In relation to the operation of the governor of a generating unit means the percentage drop in system frequency which would cause the generating unit under governor action to change its output from no load to full load.
Grid Security	Means the power system's capability to retain a normal state or to return to a normal state as soon as possible, and which is characterized by operational security limits.
Inertia	Means the contribution to the capability of the power system to resist changes in frequency by means of an inertial response from a generating unit, network element or other equipment that is coupled with the power system and synchronized to the frequency of the power system.
Nadir Frequency	Means minimum frequency after a contingency in case of generation loss and maximum frequency after a contingency in case of load loss.
Primary Reserve	Means the maximum quantum of power which will immediately come into service through governor action of the generator or frequency controller or through any other resource in the event of sudden change in frequency.
Rate of Change of Frequency or *df/dt* or RoCoF	Means the time derivative of the power system frequency which negates short term transients and therefore reflects the actual change in synchronous network frequency.
Reference contingency	Means the maximum positive power deviation occurring instantaneously between generation and demand and considered for estimation of reserves.
Resilience	Means the ability to withstand and reduce the magnitude or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, or rapidly recover from such an event.
Voltage Stability	Means the ability of a transmission system to maintain steady acceptable voltages at all nodes in the transmission system in the normal situation and after being subjected to a disturbance.

4.2. Focus on specific concepts.

What is the Inertia?

Inertia means the tendency of an object to remain in own state of motion or statics. It has historically been an important component of reliability in the electric grid.

What is the Inertia in power system context?

Power systems consist of generating units, transmission and distribution networks and load. Other than inverter-based resources, generating units consist of rotating mass rotating at synchronous speed. On the other hand, in the load side there are many motors which also rotates at synchronous speed. Inertia in power systems refers to the energy stored in large rotating generators and some industrial motors, which gives them the tendency to remain rotating. When a large generating unit trips the mechanical energy input reduce whereas the electrical output remains same, stored kinetic energy of rotating mass is very much valuable to temporarily make up for the mechanical power lost from the failed generator. This temporary response—which is typically available for a few seconds—allows the mechanical systems that control most power plants time to detect and respond to the failure.

When we talk about a single generator, we can represent the inertia mathematically as follows:

$$T_{mech}(t) - T_{elec}(t) = J\frac{d\omega}{dt} + loss$$

Where $\mathrm{T_{mech}(t) - T_{elec}(t)}$ represents the torque imbalance between electrical output and mechanical input to the generator in Newton-meter (NM). J is the inertia of the rotating mass of the generator in $\mathrm{kg - meter^2}$. ω is the angular speed of the generator.

If loss is ignored, the inertia is an effect proportional to torque imbalance and inversely proportional to speed gradient. The kinetic energy stored in the generators can be expressed as follows:

$$Kinetic\ energy\ E_k = \frac{1}{2}J\omega^2$$

If power imbalance is imposed on the generator between electrical and mechanical, then its kinetic energy changes to regain the new equilibrium. Therefore, in terms of active power the above equation may be rewritten as follows:

$$P_{mech}(t) - P_{elec}(t) = \frac{dE_k}{dt} = J\omega\frac{d\omega}{dt} \cong \omega_r * J\frac{d\omega}{dt}$$

Where, ω_r is the rated synchronous speed. Inertia(H) of a single generator is also expressed as ratio of Kinetic energy of the rotating mass to its MVA rating(S).

$$H = \frac{E_k}{S}\ MW - s/MVA = \ J\frac{\omega^2}{2S}$$

By replacing the above value of H in the equation 3.3 we get:

$$P_{mech}(t) - P_{elec}(t) = 2H\frac{d\omega}{dt}$$

In a large power system, there are many numbers of synchronous machine running in parallel. If we assume that there is only synchronous rotating generator in the system, the overall system inertia from generating units may be represented as

$$H_{sync} = \frac{\sum_{i}^{N} H_i * S_{G,i}}{\sum_{i}^{N} S_{G,i}}$$

However, in actual system there is IBR based resource and therefore the calculation of inertia may change by changing the reference to demand met in place of summation of MVA rating.

$$H_{sync}^{gen} = \frac{\sum_{i}^{N} H_i * S_{G,i}}{P_{load}(MW)}$$

Similarly load inertia should also be considered for computing total system inertia as follows:

$$H_{Total} = H_{sync}^{gen} + H_{load}$$

Total Kinetic energy stored in the grid may be represented as follows:

$$E_{K\ Total} = H_{Total} * P_{load}(MWs)$$

What is Rate of Change of Frequency (RoCoF)?

Rate of change of frequency (RoCoF) is the time derivative of the power system frequency (df/dt): it is an important quantity that qualifies as the robustness of an electrical grid.

The initial value of the df/dt is the instantaneous RoCoF just after an imbalance of power in the electrical power system (i.e. disconnection of a generator/load tripping), before the action of any control. RoCoF is calculated as follows:

$$RoCoF|_{t=0+} = \frac{\Delta P_{mismatch}}{P_{load}}\frac{f_0}{2H}$$

where t=0+ is the moment just after disconnection of the load/generation

What is Centre of Inertia?

The classical approach in studying electromechanical transients in a system is the nodal representation of the grid, describing with proper dynamic equations all the rotating machines and loads.

A complete nodal model has for output a simulation of N frequencies in physical selected busbars; it is evident also from real measurements (i.e. WAMs) that each measurand location has its local frequency. In frequency transient stability studies, in order to describe the transient behaviour of a system with N generators, it is convenient to use the concept of Centre of Inertia (COI), defined as the inertial centre of all the generators. The position of COI (i.e. the rotor angle of the COI) is defined as follows:

$$\delta_{COI} = \frac{1}{H_T}\sum_{i=1}^{N} H_i\delta_i$$

where H_T is the sum of inertia constants of all N generators in the considered system and is the rotor angle of the generator with index i.

What is Stability?

Power system stability is defined as "the ability of the system, for a given initial operating condition, to return to a state of operating equilibrium after a physical disturbance, with most of the variables of the system constrained so that the entire system remains intact" [1]. This definition underscores the system capacity to endure both minor disturbances, such as load variations, and, more significantly, major disturbances like generator failures or critical high voltage transmission line short circuits. These events bring about substantial structural changes with evident implications for the system stability.

Conducting studies and ongoing analyses of the power systems are crucial for implementing appropriate planning measures. However, designing a power system that can withstand every single or multiple contingencies, ensuring robustness against any disturbance event, is technically and economically impractical. Consequently, power system planning often involves striking a proper balance between reliability and economy, focusing on events with the highest probability of occurrence or those causing severe grid perturbations.

To analyze dynamic events that could jeopardize system stability and identify effective strategies to mitigate their effects, a meticulous classification of stability forms is crucial. This classification should consider various features, including disturbance magnitude, time dynamics, involved devices, and, notably, the physical nature of the instability [1].

Recent revisions and expansions of stability classification have incorporated considerations for the grid effects of Converter-Interfaced Generators (CIG). Two additional categories, namely resonance stability and converter-driven stability, have been introduced alongside the existing categories of rotor angle stability, frequency stability, and voltage stability. This expansion was necessary because, unlike conventional generators characterized by relatively slow electromechanical phenomena, CIGs exhibit much faster dynamics, ranging from a few microseconds to several milliseconds, giving rise to complex electromagnetic phenomena [2].

Further details about this classification, schematically depicted in Figure 1, are discussed in the following subsections.

Rotor Angle Stability: the power system capability to preserve synchronism following a small disturbance (i.e. *small-signal stability*) or a significant disturbance (i.e. *transient stability*) is a critical aspect to consider in the context of power system operation. Following a disturbance, there is an imbalance between mechanical and electromagnetic torque, leading to the acceleration or deceleration of the generator rotors. This discrepancy results in an angular difference, prompting a portion of the load to shift from slower machines to faster machines. If the system fails to synchronize by absorbing kinetic energy, rotor angular instability ensues.

The change in electromagnetic torque can be categorized into two components: a synchronization torque in phase with the rotor angle deviation, the absence of which leads to non-oscillatory instability, and a damping torque in phase with the speed deviation, the absence of which leads to oscillatory instability. To satisfy a stability condition, both components must be present for each synchronous machine connected to a power system.

Frequency Stability: This pertains to the power system capability to maintain the frequency close to the nominal value following a substantial imbalance between generation and load. Achieving frequency stability involves proper coordination of control and protection devices. It can be categorized into short-term and long-term frequency stability based on the timing of the event. Frequency stability is intricately linked to rotor angle stability, given the relationship between rotor speed and grid frequency. It's noteworthy that during frequency excursions, voltage fluctuations can be significant, potentially leading to untimely or poorly coordinated operation of protection systems [3].

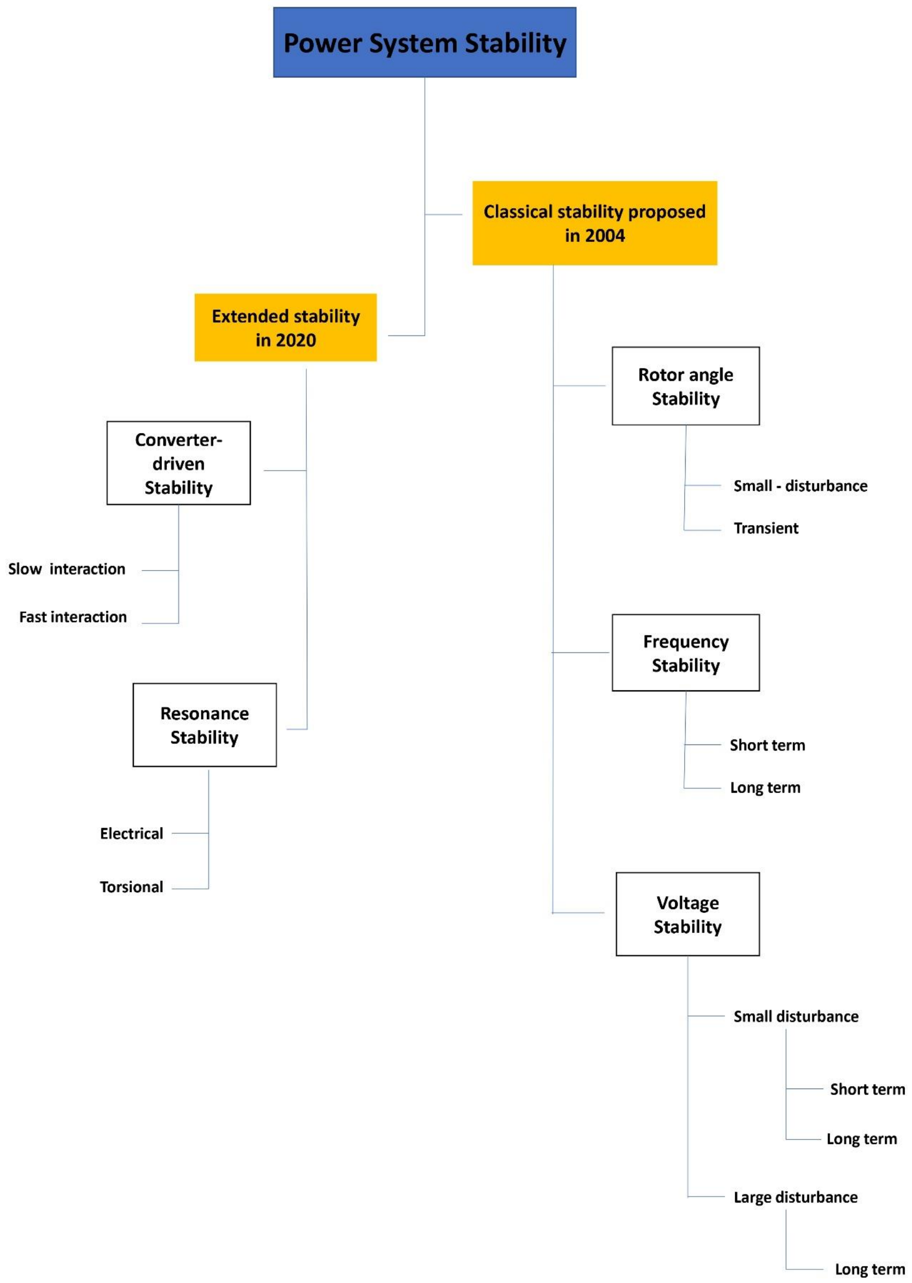

Figure 1: Power System Stability Classification (2004) and subsequent extension (2020) performed by the Task Force by the IEEE Power System Dynamic Performance Committee and the CIGRE Study Committee 38.

Voltage Stability: This refers to the power system ability to sustain voltage magnitudes at all buses as close as possible to the nominal value following a disturbance. Voltage instability may result in a drop or rise in voltage at certain buses, posing risks of cascading outages or load losses. The key factor here is maintaining or restoring the balance between load demand and supply [2]. Voltage stability can be further divided into two subcategories: one considers the magnitude of the disturbance (i.e. voltage stability for small and large disturbances), while the other distinguishes the duration of instability (i.e. short-term and long-term voltage stability). Voltage stability is significantly load-dependent, as disturbances lead to an increased load on the high-voltage grid to restore power consumption, surpassing the transmission and generation system capacity, leading to higher reactive power consumption and voltage drop [4]. While voltage reduction is the more common form of voltage instability, overvoltage instability is also possible, mainly caused by network capacitance hindering reactive power absorption by synchronous compensators [5].

Resonance Stability: Resonance occurs when energy exchange follows an oscillatory pattern. If oscillations surpass predetermined thresholds, there's a risk of resonance instability. Depending on whether resonance manifests mechanically (torsion of the drive shaft) or electrically, further distinctions are made [2]:

- **Torsional Resonance**: This type of resonance arises from torsional interactions between series-compensated lines and the mechanical shaft of the turbine generator. Vibrations generated by interactions between fast-acting control devices and system stabilizers can be poorly damped, undamped, or negatively damped and increasing, posing a threat to the mechanical integrity of the shaft.
- **Electrical Resonance**: This type of resonance occurs in certain generator types susceptible to self-excitation. The series-connected capacitor forms a resonant circuit with the actual inductance of the generator at sub-synchronous frequencies. This resonance leads to significant currents and voltage fluctuations, potentially causing damage to the generator's electrical equipment and the transmission system.

Converter-Driven Stability: Unstable oscillations can arise in the system due to cross-couplings with the electromagnetic dynamics of machines and electromagnetic transients in the network. These couplings primarily result from the fast dynamics of the converter controls underlying CIG. Depending on whether interactions are slow (less than 10 Hz) or fast (10 to hundreds of Hz), the phenomena can be further classified based on frequency levels [2]:

- **Stability of Converters with Fast Interactions:** These interactions can induce oscillations at high/very high frequencies (hundreds of Hz to several kHz), termed harmonic instability. An example of such instability is observed in the controllers of synthetic inertial systems.
- **Stability due to Slow-Response Inverters**: Dynamic interactions involve control systems of power electronics devices with slow-response system components.

5. Scenario Analysis

The current electricity mix is still dominated by synchronous generation. Of the nearly 30,000 TWh of electricity produced worldwide in 2022, synchronous generation will account for 88% of the total [6].

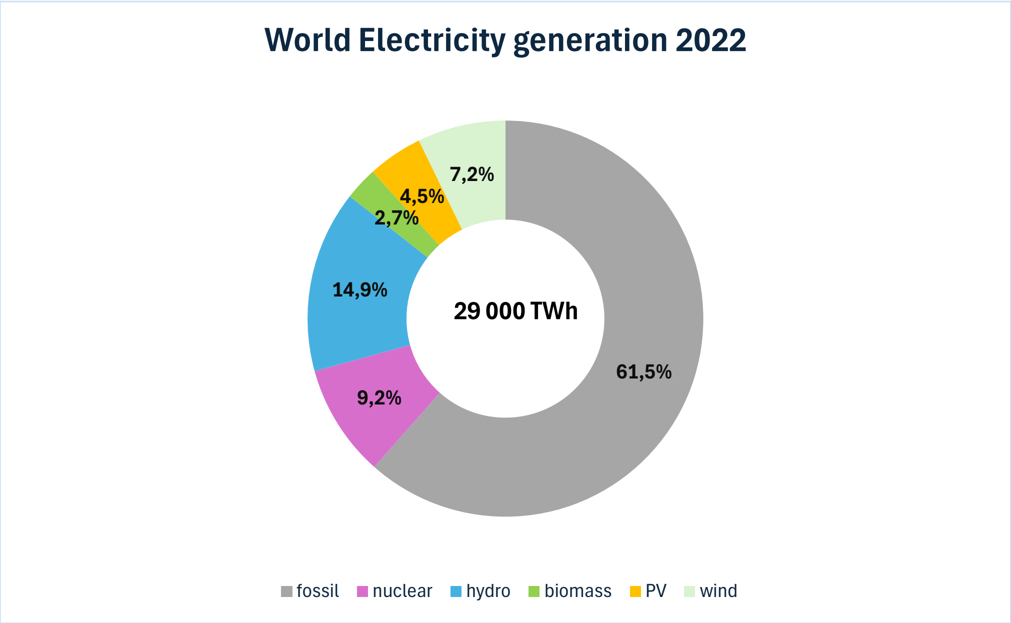

Figure 2: Breakdown of electricity generation worldwide by fuel in 2022 (source world energy data).

With only 11.7% of the total, intermittent solar and wind generation are still minor. As a result, the reduction in inertia remains low (see figure 2).

The growth in the world's population and economy, coupled with urbanization, will result in a substantial increase in energy demand over the coming years. The United Nations (UN) estimates that the world's population will grow from 7.8 billion in 2020 to around 9.7 billion by 2050. At the same time, the decarbonization of energy will mean replacing fossil fuels with cleanly produced electricity, therefore solar and wind power set to play a larger role in the electricity mix in the future.

Projections indicate that the global installed capacity of electricity generation from wind and photovoltaic generators is expected to reach approximately 3.8 TW by 2030 and more than 20 TW by 2050 [7].

Forecasts for 2050 vary from one study to another. However, all stress the importance of intermittent sources, such as solar and wind power, for the future.

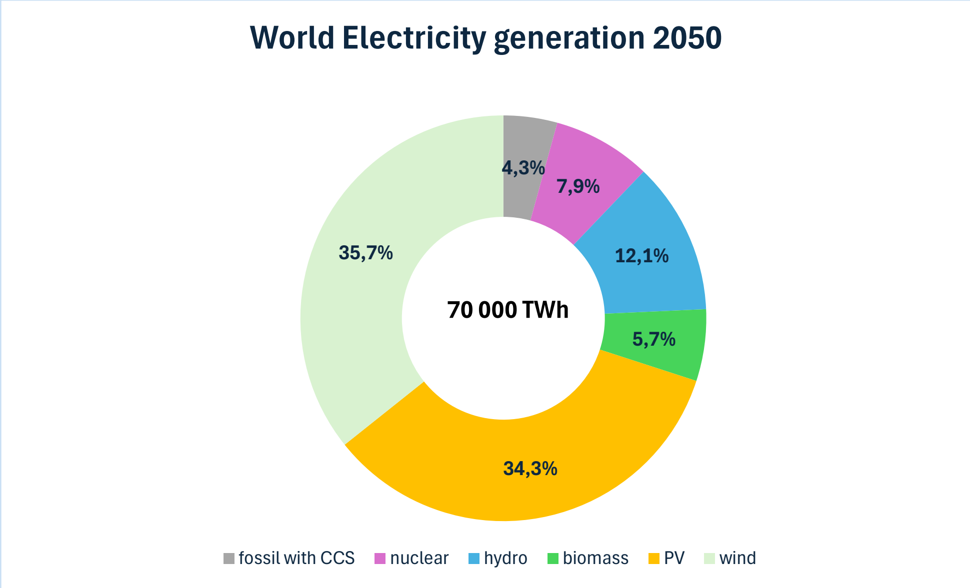

Figure 3: Breakdown of electricity generation worldwide by fuel in 2050 (source IEA).

Figure 3 shows the breakdown of electricity generation according to the IEA study Net Zero by 2050 - a roadmap for the global energy sector [7]. In this situation, synchronous electricity generation, from fossil sources with carbon capture and storage (CCS), nuclear, biomass and hydro sources, would account for 30% of the electricity mix. With 70%, the dominant share of electricity is expected to come from wind and solar power.

Therefore, mitigating the impacts of climate changes, depleting fossil resources, and increasing energy demands of developing nations has resulted in a significant surge in the adoption of renewable power generators connected to transmission and distribution grids through power electronic converters. The major deployment of power electronics to connect these intermittent sources should contribute to a significant reduction in system inertia.

So, while the reduction in inertia is not yet detectable, it should become more significant in the years to come with the development of PV and wind sources.

6. TSO challenges for guaranteeing stable system operation

6.1. Stability in low inertia power systems

As already recalled, the large-scale integration of power electronic converters in modern power transmission systems, especially in the context of Converter-Interfaced Generators (CIG) expected to replace conventional Synchronous Generators (SG) in the medium to long term, demands careful analysis. The distinctions between CIGs and SGs, including significantly lower nominal power, zero inertia for static generators, limited active power regulation for renewable power generators, and extremely faster dynamic response, introduce challenges that diminish grid flexibility, increase vulnerability to dynamic perturbations, and complicate power system stability analysis.

In this context, the management of uncertainties resulting from the intermittent nature of renewable power generators is a major challenge. The power profiles of these generators are not predictable as they depend on the dynamics of the energy source like wind speed and solar radiation. Although some predictions can be made, significant forecasting errors often occur, complicating power system operations.

Moreover, low inertia power systems have different time scales for their dynamics compared to conventional power systems. The dynamics of the former can go as low as 10^{-4} or 10^{-6} seconds, which leads to undesirable dynamic coupling, especially in high R/X ratio networks (e.g. power distribution systems). Such systems also have low tolerances to frequency and voltage deviations, which could lead to frequent grid disconnections and dynamic perturbations [8].

Low inertia power systems also have low short-circuit current, which poses a significant challenge to power system protection systems. Indeed, in a network with high CIG penetration, there is no sub-transient period during a short-circuit event, which necessitates the modification of protection and control devices.

Non-linear effects resulting from the power converters' discrete switching operation or saturation should also be analyzed carefully, as they can trigger cascading events in the protective systems. Special functions like low and high-voltage ride-through may be required to prevent these events [8].

All these phenomena are expected to increase frequency deterioration, whose magnitude depends on the actual value of the system inertia. Hence, since the balancing functions are strictly influenced by frequency measurements, the amount of flexible resources required to guarantee system stability in a low inertia system would be larger, fostering the concept of the economic value of inertia.

The provision of inertia is closely related to the on/off binary variable of a generator. Unlike energy, the inertia provision of a synchronous generator does not change continuously. Irrespective of whether a generator is operating at full or partial load, its inertia provision remains constant.

However, if energy is provided by multiple partially loaded generators instead of a few fully loaded ones, the associated costs are expected to increase.

Additionally, the value of inertia is directly proportional to the instantaneous power generated by renewable power generators, as the risk of unstable operation increases with higher renewable energy production.

The economic losses incurred when the frequency nadir and maximum RoCoF constraints are not met help in assessing the value of inertia provision. It is crucial to establish suitable values for acceptable frequency nadir and maximum RoCoF, which consider both the economic aspects and instability risks.

The value of inertia is expected to vary over time, depending on the dispatch results and the amount of energy produced by renewable power generators. In an hour marked by lack of energy production from several large thermal and hydropower plants, the value of inertia provision could be low. If the inertia on the system is low, the value of the inertia provision should be higher due to the increased risk of instability.

In low inertia systems, inertia provision can add value by reducing economic losses from renewable energy curtailment due to stability reasons. It is essential to note that the RoCoF mainly depends on inertia, while load damping and controls also impact the frequency nadir thus highlighting how power system stability deals with an intricately complex set of issues.

Furthermore, the value of inertia provision decreases progressively as higher amounts of extra inertia are added to the system, as the risks of instability are gradually reduced.

6.2. Enabling technologies for secure operation

6.2.1. Inertia estimation and usage in planning and dispatching applications

Power systems decarbonization is stimulating the massive deployment of Renewable Power Generators (RPGs) in existing electrical grids, as confirmed in [9], which clearly indicates a sensible increasing of RPGs contribution to the overall generation mix and, in particular, an average yearly (worldwide) growth rate of 15% for photovoltaics and 10% for wind generators [10].

In this new scenario, a significant issue to address revolves around the persistent decrease in mechanical inertia from Synchronous Generators (SG), which can be defined as the ratio of kinetic energy to the generator rated power. Indeed, system inertia serves as a valuable grid resource for mitigating frequency fluctuations during the initial stages following a power imbalance, well before the activation of primary frequency control (PFC) [9].

This important feature does not characterize renewable generators, which are frequently connected to the grid by power converters-based interfaces that decouple the generator dynamics from the grid frequency. Consequently, the replacement of SG by RPGs poses major challenges to frequency regulation and Stability, such as higher and faster Rates of Change of Frequency (RoCoF), which could result in unintentional tripping of over/under-frequency relays [11].

Such fast variations in RoCoF are extremely dangerous because they reduce the time that generator controllers must intervene before the frequency reaches trip thresholds causing untimely tripping of protection systems and reducing the effectiveness of load shedding techniques [9].

The current Rate of Change of Frequency (RoCoF) standard for number of power systems is from 0.5 Hz/s to 1 Hz/s as defined in the Grid Codes. Entso-E recommends that with some of the current technologies RoCoF values above 1 Hz/s are unsustainable because unstable behaviors can lead to blackout [12]. However, due to the high penetration of FER the RoCoF of 1 Hz/s is not guaranteed and may even reach values high up to 2.5 Hs/s or even greater.

Various techniques have been suggested in the literature to address this challenging problem. The primary concept involves enabling inverter-based generators to contribute to grid support by delivering frequency regulation services, encompassing rapid frequency regulation and virtual inertia [13].

The application of these advanced functions necessitates the real-time estimation of the current power system inertia. This enables system operators to design proper control measures intended to enhance system stability and security, thereby alleviating the impacts of the significant uncertainties introduced by RPGs [14].

In this context, the development of Digital Twins (DTs)-based tools represents one of the most promising enabling technologies. DT can be defined as "a set of virtual information constructs that mimics the structure, context and behavior of an individual or unique physical asset, that is dynamically updated with data from its physical twin throughout its life-cycle, and that ultimately informs decisions that realize value" [15]. Another useful definition of DT is "an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin" [16].

Therefore, DT-based tools have the capability to simulate the dynamics of complex systems in actual operational scenarios by effectively combining information derived from both physical and data-driven models [17]. This attribute proves especially advantageous in the context of power system inertia estimation, given the abundance of data streams generated by time-synchronized grid sensors, resulting in a data rich but information limited operation domain.

The development of DT-based tools for system inertia estimation requires the selection of the most suitable models, which can be classified into two broad categories, namely model-based and measurement-based approach [18].

Model-based approaches have been extensively employed for inertia estimation; however, their accuracy is heavily dependent on the precision of the chosen model. Additionally, these methods may face challenges in estimating the virtual inertia contribution from inverter-based generators and storage systems when the control schemes of these devices are unknown [19].

As far as the measurement-based approaches are concerned, they have been enabled by the widespread use of Phasor Measurement Units (PMUs), which are capable of measuring both frequency and current/voltage phasors in real-time and in a synchronized manner, reaching up to 60 samples per second [20]. Such methods are widely analyzed in the literature and can be in turn classified into: (i) ambient data-based methods, which allow obtaining a continuous inertia estimation, and (ii) large disturbance-based methods, which allow estimating the parameters of the swing equation by processing the RoCoF and power change measurements recorded for a short time window following a severe disturbance.

Concerning measurement-based approaches, their implementation has been enabled by the extensive use of PMUs. These units have the capability to real-time and synchronously measure both frequency and current/voltage phasors, with sampling rates reaching up to 50-60 samples per second [20]. These methods are extensively discussed in the literature and can be categorized into two main types:

- ambient data-based methods, providing continuous inertia estimation.
- large disturbance-based methods, which estimate swing equation parameters by analyzing RoCoF profile and grid measurements recorded during a brief period following a significant disturbance.

In particular, the approach presented in [21] introduces a methodology for categorizing and estimating non-synchronous inertia within an AC microgrid. This involves the identification of a parameter matrix capable of pinpointing the non-synchronous inertial response of the system. The estimation method follows a multi-step process, with a focus on enhancing accuracy by introducing the concept of “releasable kinetic energy”.

In [22], a method for estimating both inertia and damping coefficients in power systems with mixed generation is developed, taking into account both Primary Frequency Control and Fast Frequency Regulation. The proposed approach, which is based on scalar regression models, exhibits good accuracy and is suitable for online application. However, when estimating the overall inertia of the entire area, significant errors arise, prompting the recommendation of a distributed approach that locally estimates heterogeneous inertia.

In contrast, [23] proposes an inertia estimation method using PMUs. Instead of defining an area through traditional consistency criteria, it establishes an area based on the locations of available PMUs in the network to construct a dynamic equivalent network. Inertia is then estimated by solving the oscillation equation through the least-squares method. While this method demonstrates good accuracy, analyzing a large area makes the results highly dependent on the number and location of installed PMUs.

To leverage the capabilities of PMUs, [24] introduces a methodology for estimating not only inertia but all parameters affecting inertial response, including damping coefficients and droop parameters. This is achieved using first- and second-order AutoRegressive–Moving-Average models with eXogenous inputs (ARMAX). Unfortunately, the accuracy of these ARMAX-based models is influenced by factors such as noise levels, time window size, and the penetration ratio of Renewable Energy Sources (RES).

To overcome these issues, data-driven-based techniques, which allow to directly estimate the power system parameters by dynamic optimization, can be integrated in the grid DT and adopted for estimating the system inertia from PMU measurements. The potential advantages resulting from the utilization of this optimization-driven model primarily stem from its capacity to reliably and accurately model of the actual frequency response of the power system, thereby enhancing the precision of inertia estimation in the power grid. These attributes position the suggested paradigm as a promising research direction for developing a Digital Twin of interconnected power systems.

With the aim to assess the inertia value in long-term planning the Inertia Constant (H) can be calculated. The generators and motors connected synchronously to power system shall be include in inertia calculation.

The inertia constant H describes the inertia of an individual turbine-generator:

$$H = \frac{1}{2} \cdot \frac{J\omega_n^2}{S_n} \text{ [s]}$$

where
J is the moment of inertia of a generator and turbine [kg·m2],

ωn is the rated mechanical angular velocity of the rotor [rad/s],

Sn is the rated apparent power of the generator [VA].

The inertia constants and rated apparent powers of individual turbine-generators can be used to calculate inertia of a power system

$$H_{sys} = \frac{\sum_{i=1}^{N} S_{ni} H_i}{S_{n,sys}}$$

where $S_{nsys} = \sum_{i=1}^{N} S_{ni}$, S_{ni} is the rated apparent power of generator i [VA]

Hi is the inertia constant of turbine-generator i [s].

The kinetic energy stored in rotating masses in MWs can be calculated using following equation:

$$E_{ksys} = S_{nsys} H_{sys} = \sum_{i=1}^{N} S_{ni} H_i \text{ [MWs]}$$

The following data can be used for inertia online estimation:

- List of switched on generators,
- Planning production values,
- Online telemetry from generating equipment,
- Circuit breaker position
- PMU data.

The total kinetic energy can be calculated as a summation of all generators based on the data above using SCADA system.

Along with this, the following uncertainties of inertia estimation should be considered:

- Not all generators could have telemetry or inertia constant value,
- The load factor and contribution from load often not considered.

A sample procedure for inertia calculation using PMU data during large disturbance is given below:

The steps followed for inertia estimation based on the above procedure are described below:

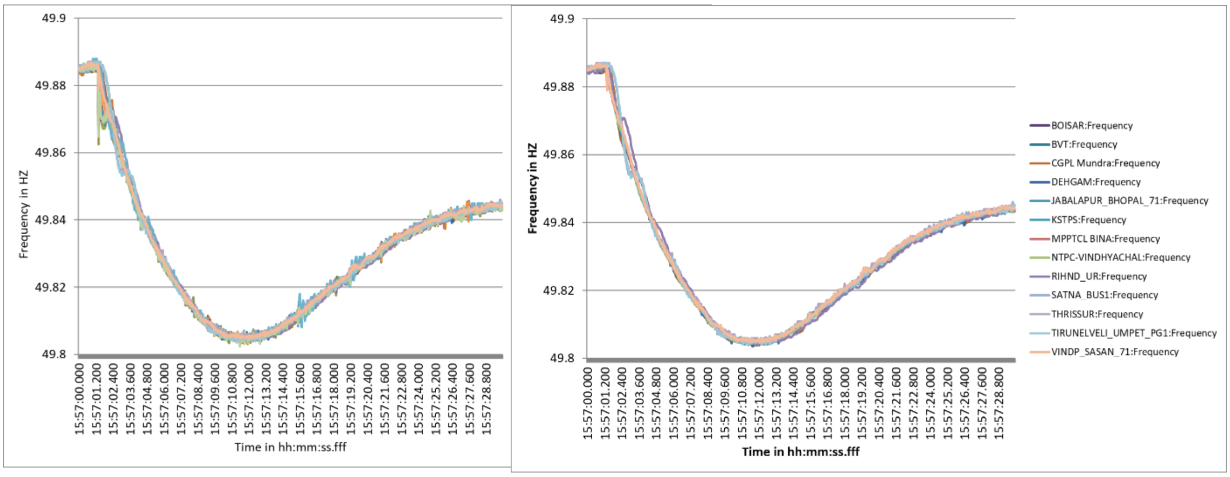

Figure 4 - Curve fitting of frequency response

Step 1: All Indian Frequency Plots from PMU measurement and All India generation prior to the event from SCADA are obtained.

Step 2: PMU data is filtered for a smooth frequency plot.

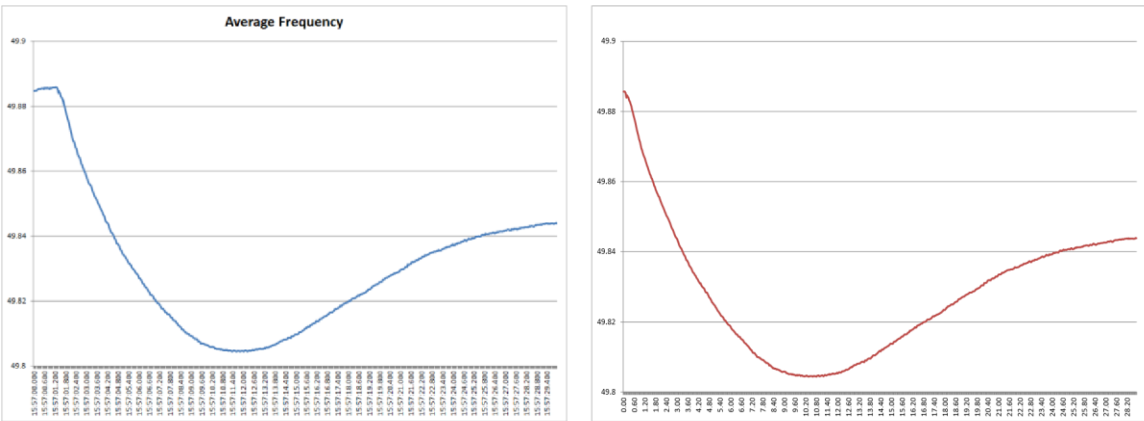

Figure 6 - Determination of pre-disturbance frequency and frequency window

Step 3: Average Frequency of these PMU data calculated and plotted, and pre-disturbance frequency is determined.

Step 4: Frequency window starting from the onset of the event is used in curve fitting approach.

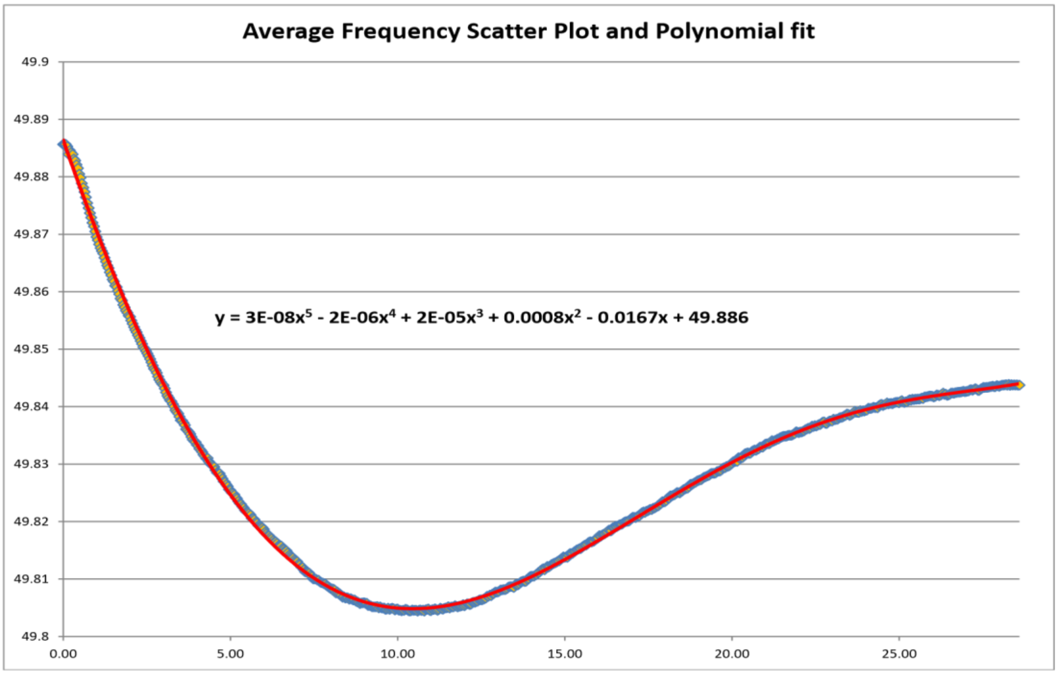

Figure 6 - Frequency response and its polynomial fit

Step 5: Using the Scatter plot and curve fitting method for 5th order polynomial to find its equation and determining initial RoCoF from the curve fit equation.

The above shown plots (Figure 4 to Figure 6) provide different information about the frequency events which is described in Figure . This includes the net frequency drop and time to reach Nadir point.

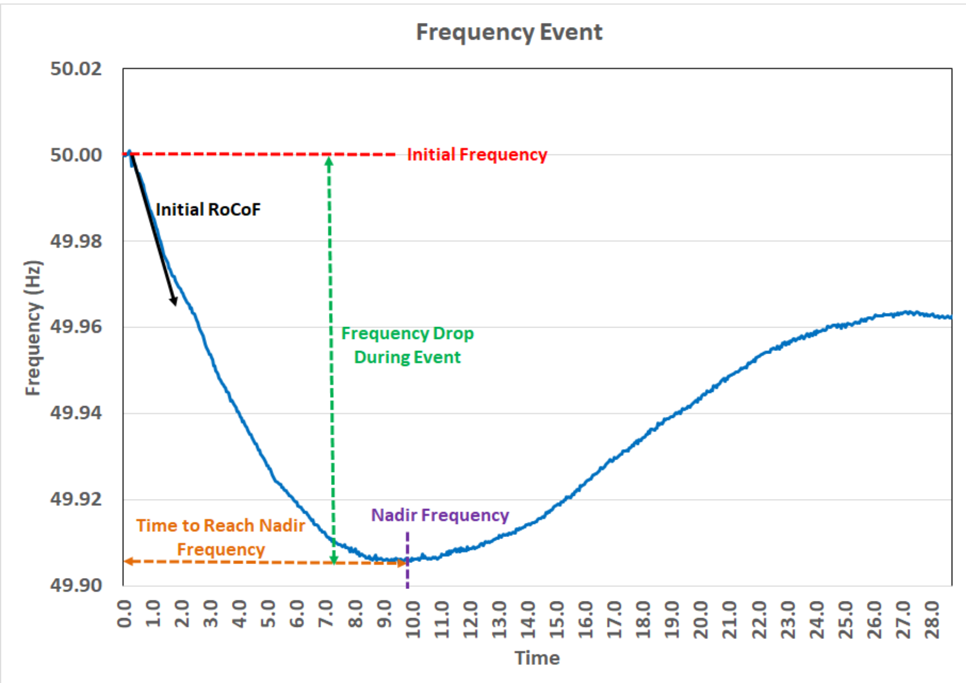

Figure 7 - Average frequency plot showing CoI frequency and other parameters

Table 2 summarises the inertia estimation related data for Indian system from the identified contingency.

Table 2 - Details of the Frequency events considered for Inertia estimation

Date and Time	21-Jan-2019 15:57
Initial Frequency (Hz)	49.885
All India Generation (From NLDC SCADA)[1] *(MW)*	144482
Actual Generation Loss (SCADA) (MW)	780
Calculated ROCOF from Avg Frequency (Hz/s)	0.0167
Estimated inertia (sec)	8.06
Nadir Frequency (Hz)	49.804
Time to Reach Nadir Frequency (sec)	10.6
Frequency Drop (Hz)	0.0810
Power Number $=\Delta P/\Delta f$ *(MW/Hz)*	9626.65

6.2.2. Technologies and methodologies for guaranteeing power system stability

Rotor Angle Stability

High penetration of CIGs significantly impacts active and reactive power flows, thereby influencing electromechanical vibration characteristics. Evaluating whether this influence is positive or negative requires an analysis of factors such as penetration level, type, location, force, operation, and the control strategy/parameters [25].

Concerning transient stability, both positive and negative effects have been documented in the literature, primarily depending on disturbance size, location, and the type of implemented control [26][27]. Generally, several case studies report positive effects of CIGs on transient stability due to enhanced flexibility in active and reactive power control [28].

The presence of High-Voltage Direct Current (HVDC) converters also strongly influences power system stability. For instance, [29] suggests installing an additional Power Oscillations Damping (POD) controller to address inter-area oscillation modes induced by HVDC lines. To mitigate higher frequency oscillations, improvements to POD controller design are necessary, avoiding unwanted interactions with modes of a different nature [30]. Reference [31] proposes a control strategy based on a combined approach, identifying the desired value of synchronization power through a model-based approach. This approach enhances both inertial and frequency response, as demonstrated by detailed simulation studies in realistic operational scenarios.

[1] It is to be noted that NLDC SCADA while having observability of most the conventional generation sources, some embedded generation, particularly of low capacity is not captured in the SCADA data. The estimation approach will be further improved by accounting for such generation in the future

Given that unstable oscillations can lead to system collapse, real-time power system monitoring is crucial for reliable assessments of system stability. PMUs facilitate advanced monitoring functions for early detection of dynamic perturbations. Modal analysis for damping estimation, as employed by the Finnish power system operator [32], is one such application. Additionally, [33] proposes a decentralized architecture for real-time monitoring using PMUs, emphasizing the advantages of this approach in detecting local oscillations. PMUs can also anticipate dangerous oscillations, as demonstrated by [34], which processes PMU measurements to estimate and classify oscillation components, including frequency and damping.

Wide Area Measurement System (WAMS) technology is another enabler for monitoring inter-area oscillations. Reference [35] underscores the advantages of using WAMS technology over conventional Power System Stabilizers (PSSs), particularly in analyzing a wide-area control technique modulating active power injections to damp critical frequency oscillations, including inter-area oscillations and transient frequency swing. WAMS technology allows multiple remote signals for designing effective control strategies, providing greater robustness compared to local signal processing. Reference [36] assesses the benefits of installing a wide-area power oscillation damper that simultaneously damps forced oscillations and inter-area modes, using an event-triggered strategy to activate the adaptive control scheme. Time-synchronized measurements enable the development of Wide-area Damping Controllers (WADC) to damp inter-area oscillations, enhancing grid observability and controllability [37].

Restoration tests, involving measurement campaigns analyzing low-frequency oscillations (LFO) in active power, reactive power, and voltage magnitude profiles, are an effective method for assessing grid resilience and the correct operation of main grid components. [38] focuses on the mutual coupling between the restoration path and the transmission grid in normal operation, identifying key parameters influencing LFO amplitude and phase through electromechanical simulations.

[39] proposes a tool for detecting synchronization torque deficiency as a preventive method against aperiodic rotor angle instability due to small disturbances (ASD). Identifying potential buses influencing ASD generator stability is achieved through a Thevenin impedance analysis and sensitivity analysis based on self-propagating graphs, leading to optimal mitigation measures.

Frequency Stability

The substitution of large synchronous generators with CIGs results in a significant reduction of power system inertia, posing a potential threat to frequency stability, particularly with the surpassing of critical penetration levels by wind and photovoltaic systems [3]. Reduced system inertia leads to higher rates of change of frequency (RoCoF) and lower/higher nadir/zenith frequencies, necessitating more intricate and faster protection systems. Several technical solutions are currently under investigation, such as ultrafast control, virtual inertia, and grid-forming converter control [40]. These techniques aim to enable generators to support the grid during transient perturbations, thus enhancing frequency stability [41]. Alternatively, intentional islanding is proposed as a preventive measure to improve system resilience [42], proving effective in preventing cascading phenomena induced by High Impact Low Probability (HILP) events and facilitating the identification of pre-contingency mitigation actions.

Dynamic Security Assessment (DSA) has garnered significant attention due to its effectiveness in accurately depicting grid dynamics in the face of external and internal perturbations. Despite its offline tradition, involving Monte Carlo simulations to analyze dynamic grid evolution under "credible" contingencies, on-line deployment is challenging due to the analysis of numerous operational and failure events. However, the study [43] explores the possibility of using DSA as an "online" decision support tool through High-Performance Computing (HPC) paradigms. Case studies report successful HPC-based DSA applications, including PJM analyzing a 13,500-bus system processing up to 3,000 contingencies every 15 minutes, EPRI simulating 1,000 contingencies of a 20,000-bus system in about 27 minutes, and iTesla combining offline and online simulations [44].

To enhance power system transient stability, real-time adjustment of CIG control strategies, dynamically modulating active and reactive power profiles, is possible. The study [45] analyzes factors influencing power system transient stability and suggests a sensitivity analysis based on a multivariate optimization procedure to identify an appropriate mapping between active and reactive power profiles during grid contingencies.

Frequency stability is closely linked to power system inertia. Reference [46] introduces an "online" inertia estimation method, using World's decomposition method integrated with Goertzel's algorithm. This method employs a second-order infinite impulse response filter and logistic distributions, deploying first-order autoregressive models. The proposed method demonstrates good performance in realistic scenarios, reliably identifying actual system inertia and detecting critical operation states even with significant renewable power generator penetration. Another approach is presented in [47], which investigates the role of synchronous compensators (SC) in increasing short-circuit power to enhance voltage magnitude dynamics after severe grid contingencies, supported by detailed experimental results on real case studies.

Active Power Gradient (APG) control is a promising technique for enhancing frequency stability, as shown in [48]. The study proposes two mathematical methods for adjusting APG controller parameters to reduce frequency deviations after severe power imbalances. The methods formulate a constrained single-objective optimization problem, with the first minimizing the instantaneous variation of kinetic energy of synchronous areas, and the second minimizing spatial shifts between dynamic trajectories of temporal responses in different synchronous areas.

Voltage Stability

The extensive integration of CIGs into transmission and distribution grids introduces heightened complexity into the voltage regulation process. In this scenario, the quick dynamic response of converters poses a risk to short-term voltage stability, potentially leading to severe transient voltage disturbances, such as over/undervoltages [49].

One of the most promising strategies for enhancing voltage stability involves mitigation techniques based on synchrophasor-based data processing. These approaches leverage time-synchronized measurements acquired by a network of Phasor Measurement Units (PMUs) to detect voltage instability and implement load reduction techniques. However, the application of these methods is still in its early stages, with several open challenges requiring solution to achieve comprehensive and reliable system observability. Pertinent issues include uncertainties stemming from measurement errors, the accuracy and integrity of time-synchronization sources, and the susceptibility of PMUs to cyberattacks [50][51].

An insightful analysis of the effects induced by Doubly Fed Induction Generator (DFIG)-based wind generators on voltage stability is provided in [52]. The study identifies the impact of these generators on maximum load ability limits and the maximum scalable active power demand, highlighting that an increasing penetration of wind power generators can overload critical grid equipment, thereby constraining hosting capacity. Similarly, [53] evaluates the impact of photovoltaic generation on long-term voltage stability (LTVS). This research reveals that solar generation can have both negative and beneficial effects on voltage stability, identifying key parameters influencing LTVS, including solar irradiation, ambient temperature, inverter power, reactive power gain, and current-limiting strategies.

Another factor contributing to voltage instability is the decommissioning of conventional synchronous generators, diminishing available reactive power reserves. In this context, [54] conducts a comprehensive voltage stability analysis, calculating VQ stability margins. The study underscores the pivotal role of reactive power control strategy and reactive power capacity in converter-interfaced technologies for ensuring voltage stability. Building on this crucial insight, multiple studies recommend deploying additional devices to enhance voltage stability by improving reactive power reserves, such as synchronous capacitors, synchronous static compensators (STATCOM), switchable and non-switchable shunt capacitors and reactors, and on-load tap-changing transformers (OLTCs) [55].

Converter-driven Stability

Numerous experimental studies have highlighted the propensity of converter-driven stability issues to lead to unstable power system operations. These issues manifest through intricate dynamic phenomena, including sub-synchronous oscillations between wind generators and series-compensated lines [56] and harmonic instability induced by solar generators [57]. The genesis of these phenomena involves a complex interplay of factors, such as interactions between the control units of CIGs, power system vulnerabilities, dynamics of converter-interfaced loads, and congested power lines [58]. Specifically, the rapid dynamics of CIGs' power/voltage control units can induce swift variations in grid frequency and transient distortions of the voltage waveform, potentially triggering grid protections [59]. In light of these considerations, a meticulous analysis and categorization of all potential sources of converter-driven instabilities are paramount. This ensures the design and implementation of robust corrective measures aimed at mitigating the disruptive effects of these phenomena on the smooth operation of the power system.

Resonance Stability

Resonance stability challenges primarily arise from the torsional impacts of Flexible Alternating Current Transmission Systems (FACTS) and/or High-Voltage Direct Current (HVDC) transmission systems, along with electrical resonances originating from the grid interactions of Converter-Interfaced Generators (CIGs) controllers. Analyzing these oscillatory phenomena can be conducted through various computational techniques, such as time-domain electromagnetic power system simulation, state-space analysis, and frequency-domain impedance-based methods.

Electromagnetic power system simulation involves numerically solving the differential equations describing the dynamics of the power electronic components of CIGs. While these techniques accurately model grid oscillations, they may fall short in analyzing the intrinsic phenomena governing the oscillations [60]. State-space analysis-based methods overcome this limitation by examining the eigenvalues of the state matrix to detect unstable oscillation modes and determine the main parameters influencing their evolution [61]. However, developing a state-space model for power systems with a large number of CIGs poses a challenge, particularly in describing the reactive effects of the power transmission system and the dynamics of power electronic converters.

Frequency-domain impedance-based methods offer a promising alternative for resonance stability analysis. These methods leverage the Nyquist stability criterion of the single-port impedance, which can be developed using various modeling approaches, including small-disturbance models, harmonic linearization, and measurement methods [61]. Recently, more effective modeling approaches based on s-domain nodal admittance matrix analysis have been proposed for accurately analyzing resonance stability in power systems with a large-scale penetration of CIGs [62].

These modeling approaches help identify the main phenomena affecting resonance stability and analyze potential technical solutions to enhance grid robustness against these phenomena. Promising mitigation techniques in this context include deploying static var compensators to dampen torsional resonance and smartly coordinating CIGs controllers to dampen electrical resonance [58].

6.2.3. System Frequency Monitoring via Dynamic Modeling and Contingency Analysis

With increasing renewable penetration and retirement of traditional units in the North American Western interconnection, there has been increasing concern for system stability in real-time system operations. The RC West reliability coordinator and CAISO balancing area authority have been investing in real-time stability assessment applications over the years to incorporate generator dynamic models and other supporting data required to enable the system operator to forecast post contingency frequency response every 15 minutes in real time. With this proven capability, the CAISO/RC West collaborated with Transmission Operators and Reliability Coordinators in Western North America to establish a real time operating procedure for monitoring the frequency minimum point (nadir) for a pre-identified list of contingencies considered to have potential significant impact to system frequency and to identify cases where mitigating actions are necessary to prevent violation of minimum frequency limits. This innovation provides a watch on the interconnection to ensure maintenance of system stability during loss of large generation that could lead to stability concern and potential of under frequency load shedding in the transient time frame as the monitoring capability enables operators to initiate mitigation efforts on reported events once real time assessment results are validated.

6.2.4. Pragmatic examples of TSO projects

Online Dynamic Security Assessment
It is becoming increasingly evident that the safe management of the electric system can no longer disregard an analysis in dynamic regime of the events that are occurring or may occur on the national electric system. To face these challenges, Terna, the Italian System Operator, implemented an Online Dynamic Security Assessment (DSA) chain, which performs in real-time both static and dynamic simulations in order to be aware of the system security. In particular, the DSA automatically generates a snapshot every 5 minutes and performs more than 250 dynamic simulations for most critical N-1 and N-K contingencies. The results of the simulations are automatically interpreted, and summary information is provided to in the control room operators for enabling effective and quick decision making for implementing countermeasures. In particular, the results are displayed through a user-friendly interface, often using a traffic light alarm system.

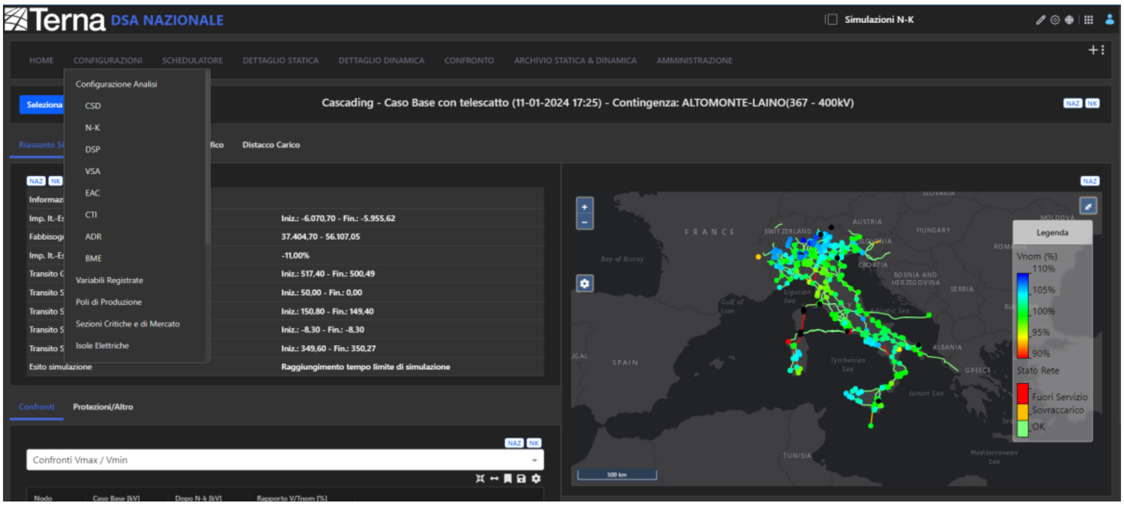

Figure 8 – Online Dynamic Security Assessment Interface.

National Grid ESO: Overview of Effective Area Inertia Metering, Forecast & Validation [63]

Today several TSOs around Europe use online inertia estimation systems. A system has been developed and now field-deployed to meter the effective inertia of the GB power system continuously and passively on a regional basis in real-time, using synchrophasor measurements. In addition, the system applies machine learning to provide forecasting of inertia, based on predictors such as anticipated levels of demand and synchronous, solar and wind generation. Both real-time metered inertia and forecast inertia for a region are automatically validated against real grid behavior each time a frequency disturbance occurs.

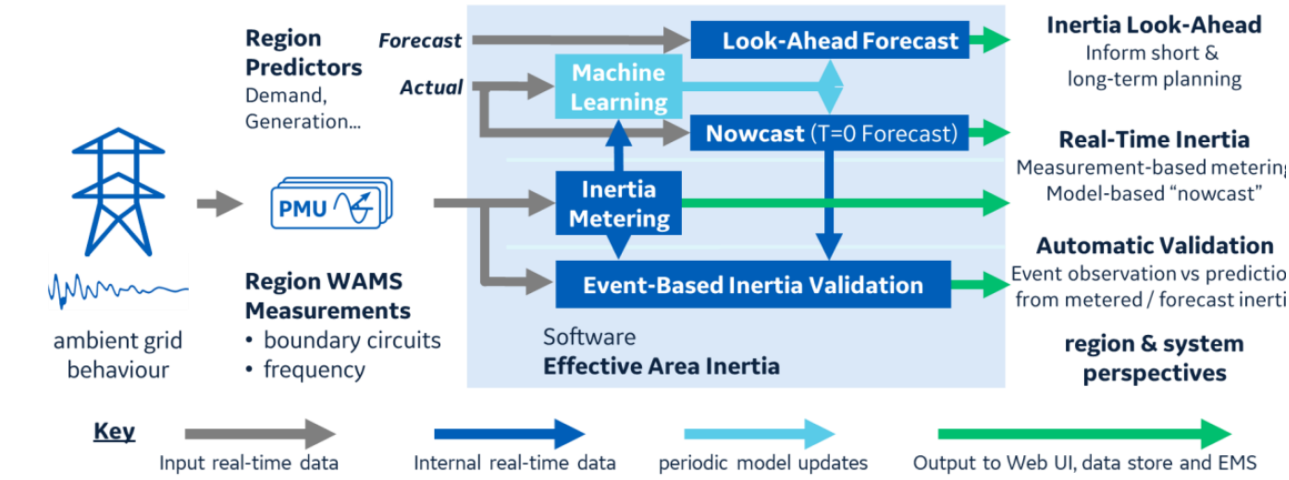

Figure 9 - Overview of Effective Area Inertia Metering, Forecast & Validation Solution

PMU data is collected by Phasor Data Concentrators at each of the three Transmission Network Owners responsible for the three transmission network areas of the GB system and streamed over an IP network via the IEEE C37.118 protocol to NGESO. The present deployment employs PMU data at 10fps.

Real-time measurements and forecasts of regional demand and generation, used for generating inertia forecasts, are received at 5–30-minute intervals from the corresponding source NGESO systems such as operational metering, the energy balancing system and energy forecasting systems.

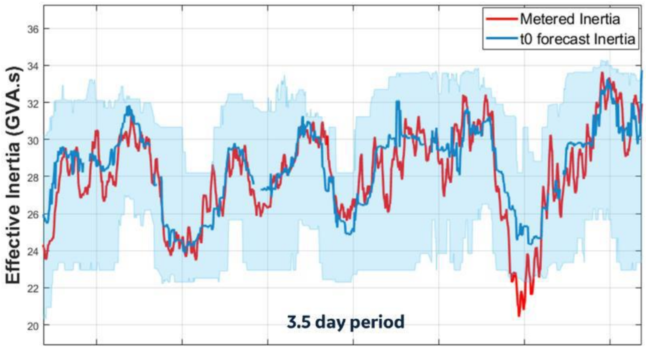

Figure 10 – Illustrative example of performance of Inertia Forecasting – shading indicates forecast confidence band

GCCIA: Special Protection Schemes

The power system in the GCC region is designed and being operated to be N-1 contingency cover. To achieve adequacy and security beyond N-1, GCCIA implemented remedial action schemes at the key nodes to increase the robustness of the GCC interconnected power system following severe disturbances including loss of large power plants. These SPS are carefully designed to keep the interconnected system intact and accordingly implemented to operate only when strictly necessary and not operate when not required.

GCCIA: Fast Reactors switching using point on wave.

To overcome the reduced reactive power reserves caused by the lesser number of synchronized conventional generators, in addition to the SVCs & STATCOMs, GCCIA is using the existing reactors and capacitors to automatically switch to overcome both leading and lagging MVAr deficiency. To protect the equipment GCCIA is using point-on-wave controllers that help in reducing switching transients and inrush currents.

ONS: Online Monitoring System

With the main purpose of increasing situational awareness, ONS has as online system that calculates inertia considering SCADA information and dynamic data for the synchronous machines in operation. Inertia values are utilized to parametrize security levels, which are based on the amount of potential generation losses, thus providing an overview of the current robustness or fragility of the power system. Additionally, dynamic contingencies, selected for their severe impact on system stability and frequency due to considerable power loss, are simulated to show the values of minimum frequency (nadir)-with a real-time basis case obtained from the state estimator.

Furthermore, the system tracks and displays historical inertia values over the years, as can be seen in the following figure, alerting users to any reduction associated with the large penetration of renewable source (wind and solar) and distributed energy resources (DERs). It also uses historical simulations of contingencies to feed a machine learning algorithm, which predicts future levels of security.

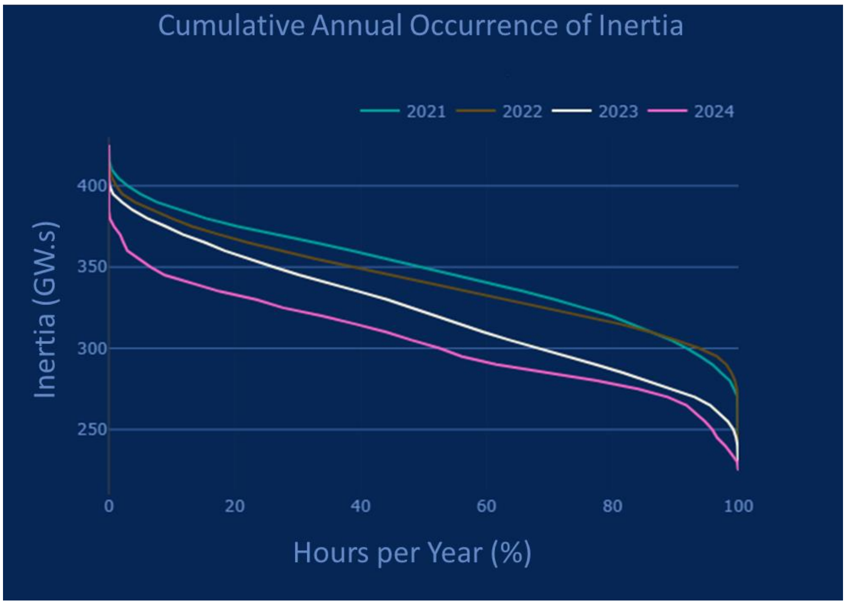

Figure 11 – Cumulative annual trends of inertia occurrences in Brazil's National Interconnected System (SIN) from 2021 to 2024, depicting the inertia in gigawatt-seconds (GWs) as a function of the percentage of annual operating hours

6.3. Innovation TSO initiatives worldwide

6.3.1. Terna: Wide Area Damping Controller

To improve observability and controllability of LFO occurring in modern power systems preventing the risk of system failure that can cause oscillatory phenomena and system instability, Terna is developing a preventive technique of Wide Area Damping Control capable of controlling a set of traditional and innovative regulating resources in order to increase the stability margins of the entire national electricity system. In particular, the function of WADC system is to process wide-area control logic by providing a stabilization signal that is injected into the main summing node of the voltage regulator of the regulating device (i.e. synchronous compensators, STATCOMs, stabilization resistors).

The WADC architecture adopted by Terna is described in the Figure 12 . It provides for the use of a Phasor Data Concentrator (PDC) to collect PMU measurements and provide the Supervisory Control with the data needed to process the set point, which is calculated by a centralized control. This set point is sent to the devices serving the WADC through a particular PMU able to interface on one side to the excitation system of the CS and on the other side to the WADC system through the protocol IEEE C37.118.

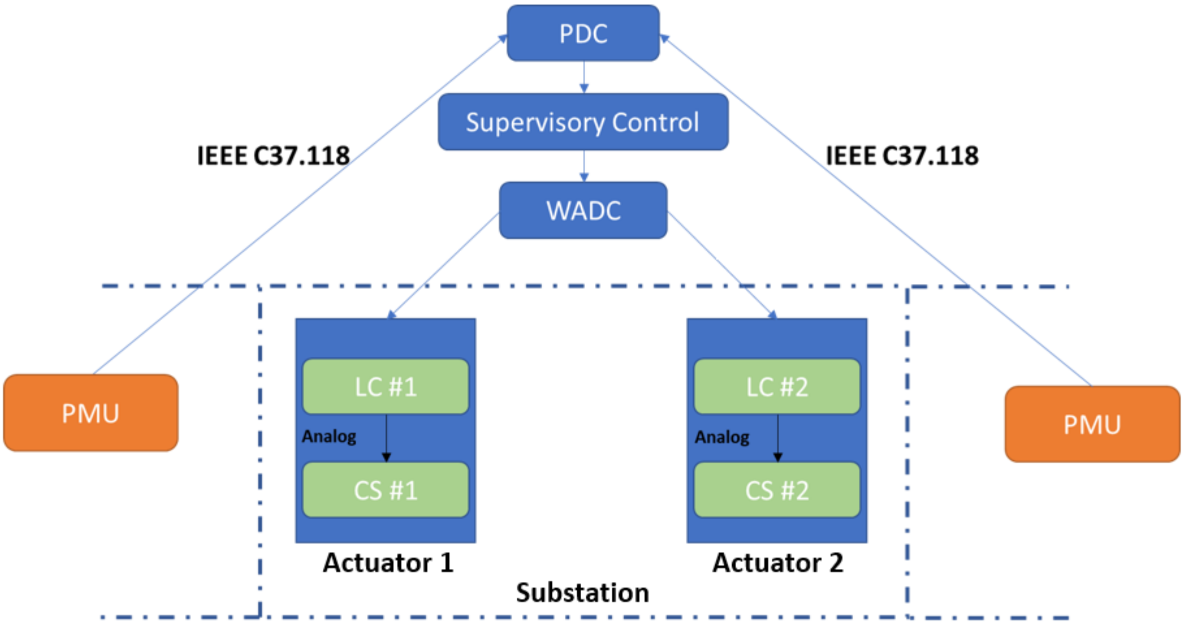

Figure 12 - Wide Area Damping Control.

The Figure 13 shows a principle block diagram describing the integration of the set point calculated by the WADC into the CS excitation control system: the command sent by the WADC system is acquired by the conversion device which translates the digital command into an analog signal [4-20 mA]; a transducer is interposed between the conversion device and the excitation system, necessary to ensure galvanic separation between the two systems. This transducer takes an input current signal and provides a current or voltage output. The WADC set point is added to the AVR as shown in the block diagram in Figure 13.

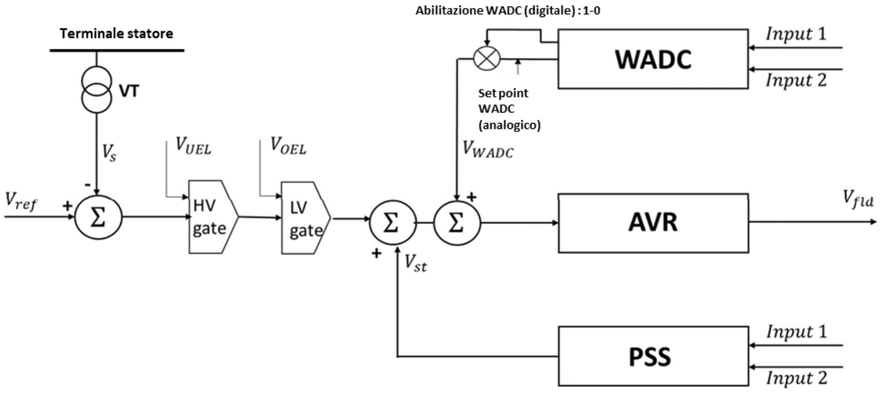

Figure 13 – Illustrative scheme of the integration of WADC in the synchronous compensator excitation system

The analog signal is processed by the control system only if the WADC command is active. This control enabling command is defined by the WADC system and sent to the excitation system of the CS, via the conversion device installed in the field as a digital signal. As you can see from the block diagram, the WADC set point is added to the other components of the control signal. Where possible, it is inserted downstream of the limits of overexcitation and underexcitation, so that it is also present when these limits are applied as a replacement and not as a sum of the other contributions.

These controllers, designed to work around specific operating points, could lack adaptability. Use of synchronized measurements from PMUs enables the development of an adaptive WADC system that can overcome limitations of traditional controllers.

Ad adaptive WADC system for the Italian power system is going to be implemented. The WADC system, designed to improve mitigation against small frequency oscillations, was validated through use cases referred to real events.

6.3.2. ENTSO-E: Inertia estimation in power system development process. [64]

The future needs identification in frames of TYNDP preparation consist of the maintaining system inertia issues. System inertia visualized in different TYNDP scenarios for 3 European synchronous areas, Nordic region, Continental Europe and UK and the island of Ireland. The scenarios with a higher share of renewables clearly offer lower available inertia (curves are lower and lower).

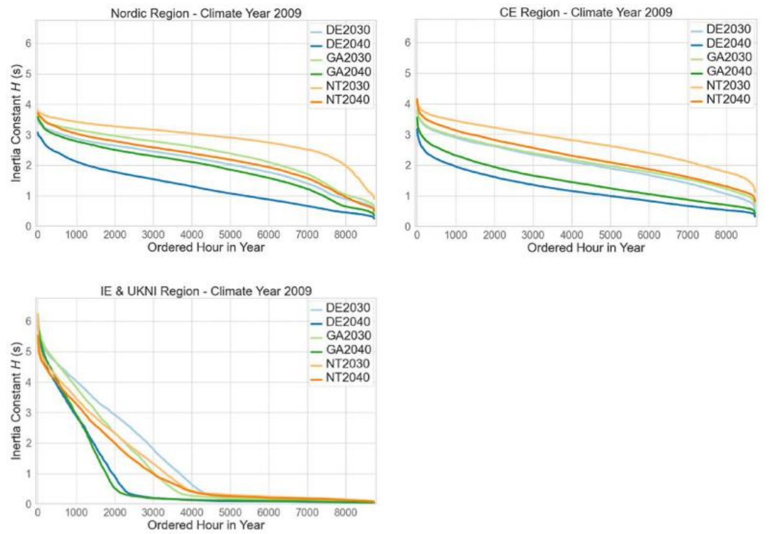

Figure 14 – System inertia visualized in the different TYNDP scenarios for 3 European synchronous areas, Nordic region, Continental Europe and UK and the island of Ireland. The scenarios with a higher share of renewables clearly offer lower available inertia (curves are lower and lower).

6.3.3. Grid India: Assessment of Inertia based on large disturbance method and its correlation analysis with various operating parameters

All India Generation vs. Grid Inertia

The Indian power system inertia has varied between 5 to 9 Seconds between Jan 2014-June 2021 as shown in Figure 1. The mean value of inertia is 6.5 seconds. It can be further observed that even though the inertia is on the higher side, the net inertia is reducing even with higher generation in the system.

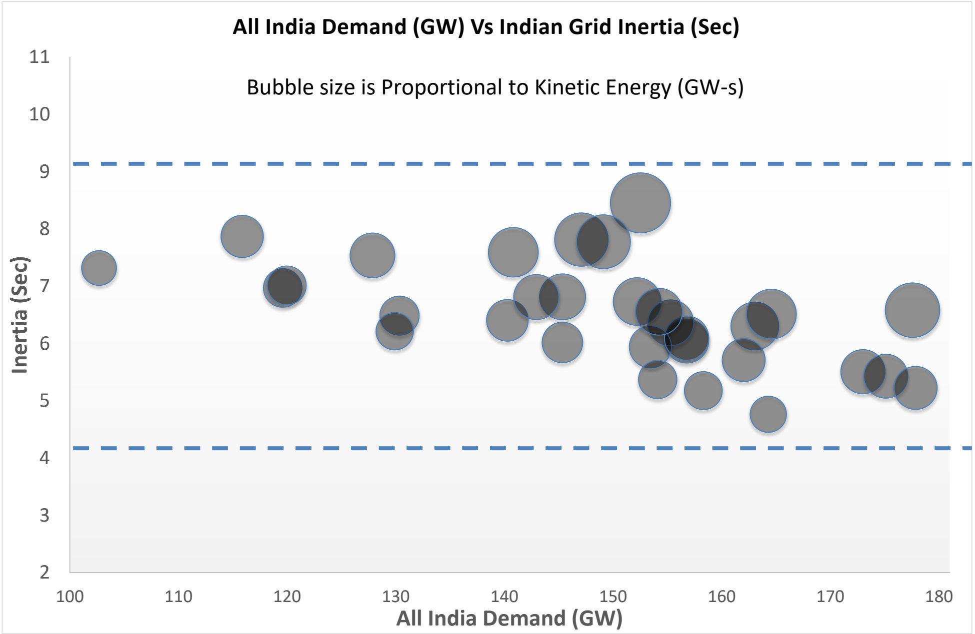

Figure 15 - All India Demand Vs Inertia for 2014-2021

6.3.4. Grid Inertia variation on year and hour scale

The Indian power system inertia calculated for the events when plotted w.r.t. year scale, it was observed (Figure 16) that over the years it has a reducing trend. Further, during the day scale if these events are plotted irrespective of years (Refer Figure 1) then, it is observed that inertia is low during the peak hours and higher in the off-peak hours. The reason attributable for this can be higher penetration of solar, lower availability of kinetic energy from the generators, a lower amount of rotating load (Agricultural load is generally connected in off-peak hours).

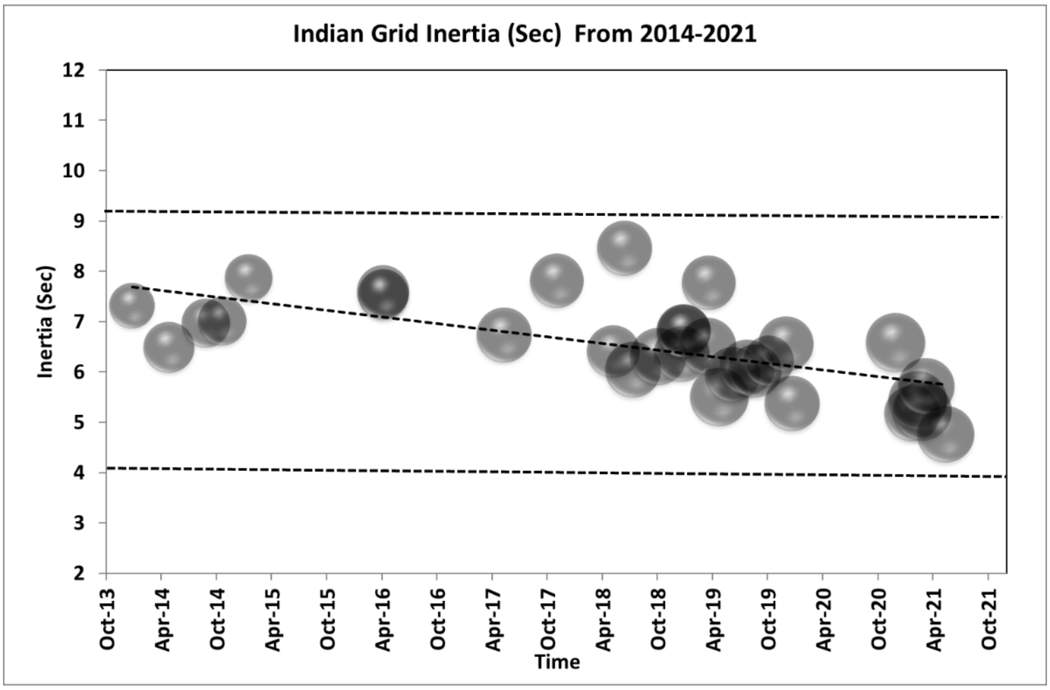

Figure 16 - Grid Inertia on Year Scale

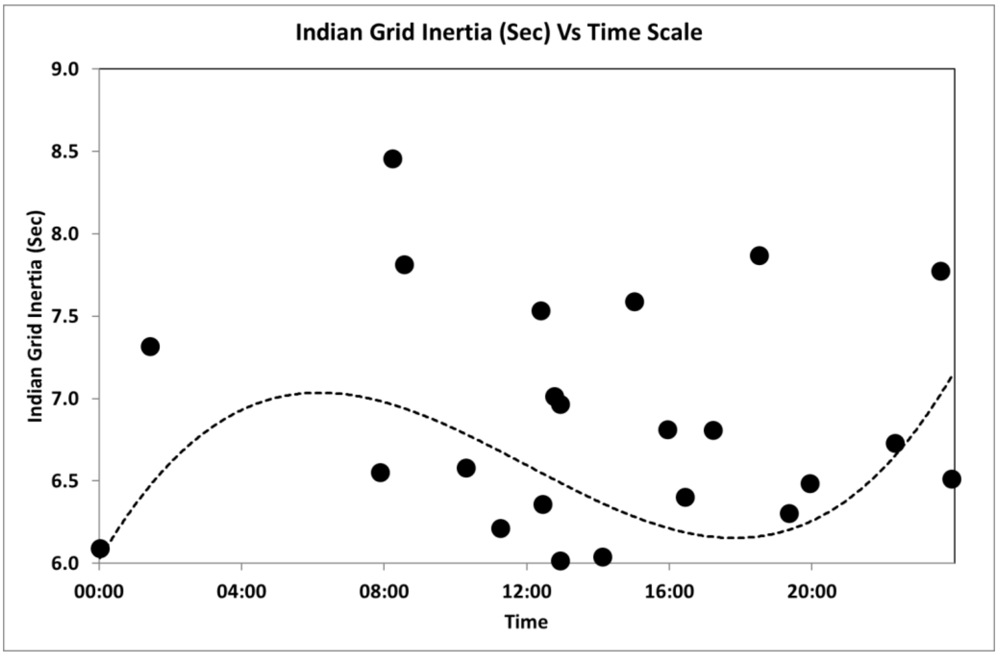

Figure 17 - Grid Inertia vs Time of Day

6.3.5. Inertia Vs. RE Penetration

Due to RE driven displacement of conventional synchronous generation, the system experiences lower system inertia. The impact of higher Renewable penetration on the system inertia in Indian grid is reflected in Figure . It is to be noted that for the period over which the plot in Figure is shown, the overall generation (including conventional generation) installed capacity of All India grid increased, however, the general trend shows that the system is becoming lighter with the increase in RE penetration assuming no contribution from renewable generation. A significant number of Type-1 wind turbine generators are installed in India that also contribute to the system inertia to some extent as they are directly coupled with the grid. However, variable speed wind turbine generators (Type-3 and Type-4) are not required to provide inertia in India.

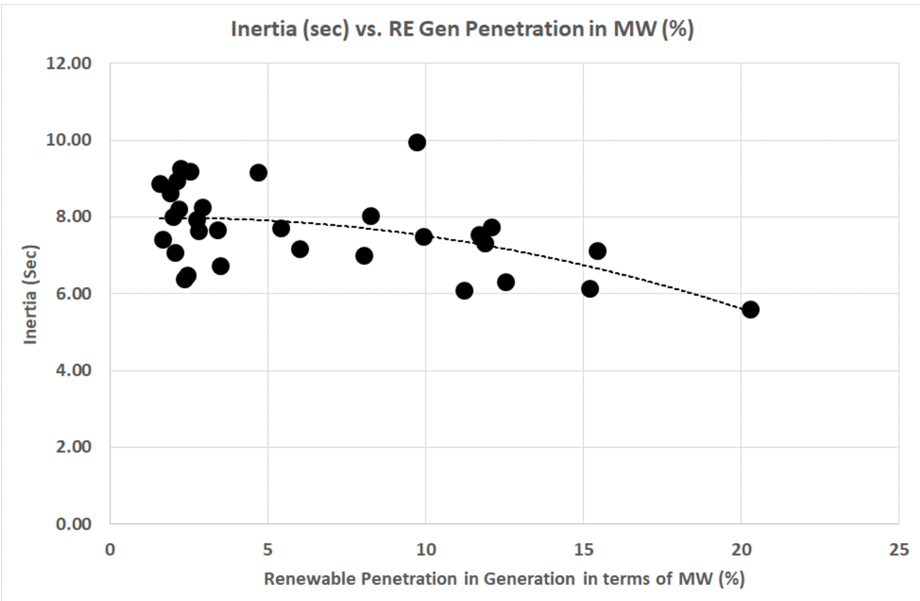

Figure 18 - RE Penetration Vs Grid Inertia

6.3.6. Generation loss vs. Total Frequency Drop

The generation loss relationship with frequency drop is also important for the system planners and operators as it helps in deciding the various defense mechanism for frequency stability in the power system. Figure 1 shows that a linear trend exists between the amount of generation loss and frequency drop observed in the Indian power system. This trend also depends also on the amount of load damping and governor. With the increase in frequency insensitive load, such as electronic or VFD based load, the slope of the overall frequency dip in Figure 1 will increase, while as case of improvement in governor response, the corresponding slope is likely to decrease.

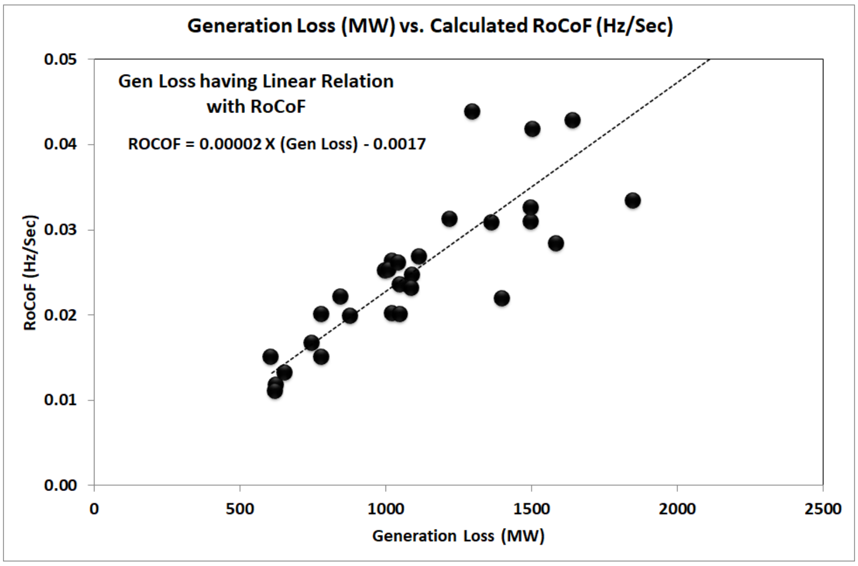

Figure 19 - Generation Loss vs. Frequency Drop

The ratio of total generation loss with the quantum of frequency fall till nadir point provides good information for system operators. This number may be referred to as power number for the Indian grid. Higher the number, more is the load damping and governor response from the system. It helps in immediate assessment of the generation loss during an event by evaluating the frequency drop, which can also help in the approximation of generation loss by automation and thus providing system operator with an alarm in case of any frequency related events. Figure shows the power number plotted for the events over between 2014 and 2021. It can be observed that it has an increasing trend over the time indicating that the governor response is improving over the years. The improvement in governor repose in the Indian power system can be visualized in the form of improvement in frequency response characteristics (FRC) for the various frequency related event as discussed in the report. However, it is important to note that the frequency response improvement in Indian grid is a combined effect of various efforts in Indian power sector that have taken place over the past several years, such as, DSM and ancillary services.

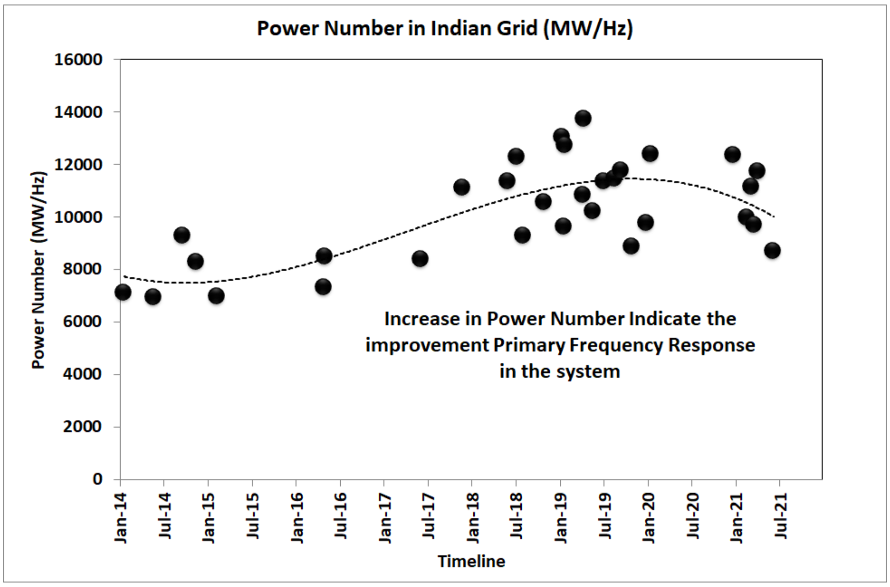

Figure 20 - Ratio of Generation Loss and Frequency drop over the time

6.3.7. Real-Time kinetic energy monitoring

The system inertia calculated at NLDC, GRID-INDIA using sum of known inertia constants can be validated using system inertia computed based on frequency disturbances. Based on validation results the online inertia estimation based on known inertia constants can further be tuned.

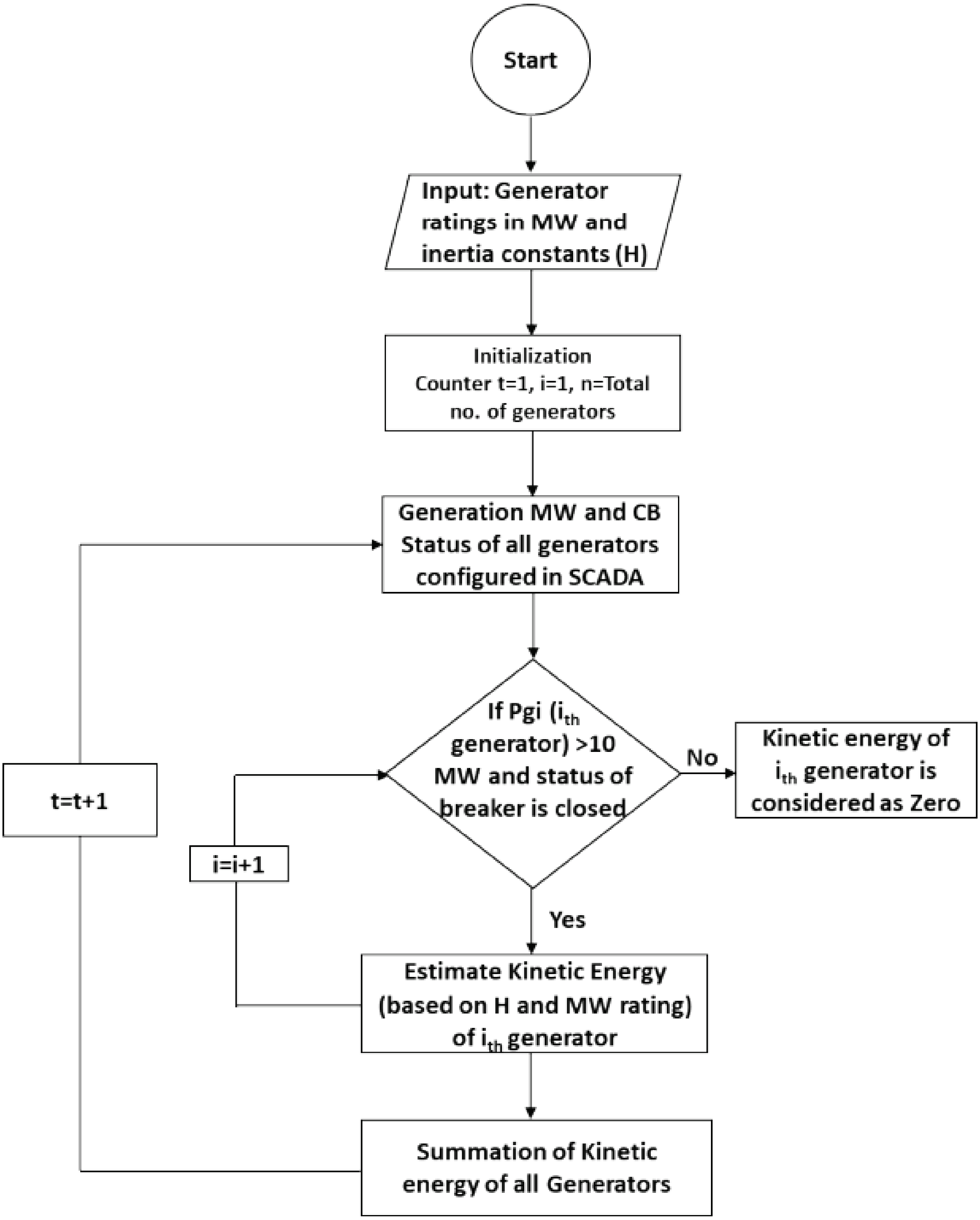

Figure 21 - Flow chart for online kinetic energy monitoring

Screenshots of online inertia monitoring tools of different control centres are shown below. Apart from kinetic energy, percentage renewable penetration, number of units online, total capacity of the units online are also indicated.

Table 2

All India Power System Inertia

16:00 hrs on 25th Nov 2021

Region	As per SCADA Data			Derived Value
	No of Units On Bar	Capacity on Bar (MVA)	Actual Generation (MW)	Kinetic Energy (Sec-MW)
Northern Region	108	34736	29695	113328
Western Region	191	69654	57479	234004
Southern Region	166	38679	37921	166010
Eastern Region	162	41900	21893	151763
North Eastern Region	50	3092	2197	9376
All India	677	188062	149185	674482

6.3.8. GCCIA: Wide Area Protection System (WAPS)

GCCIA has initiated a pilot project to use wide area protection system (WAPS) to take fast remedial actions to protect the interconnected system against fast transients as well as detection of growing oscillations may lead to out of step condition and preventive loadshedding.

The WAPS will work measuring System-wide and/or a Member State specific RoCoF through PMUs at key locations and using estimated inertia values to calculate the imbalances in MW from the measured RoCoF as well as the identification of the disturbance location based on the power flows and angle measurements.

The WAPS will make fast assessment of the transient stability limits of the respective corridors based on the pre-contingency flows and angular stress across the GCC interconnected system and will accordingly calculate the remedial action targets using the estimated loss of generation and stability limits of the respective corridors.

The WAPS will additionally verify that the triggered remedial actions are sufficiently stabilizing the network and if needed produce additional actions to stabilize the network.

6.3.9. GCCIA: Inertia Measurement & Estimation using BtB HVDC

Since the integration of renewables, GCCIA started to monitor system inertia through sum-method based on EMS data. GCCIA also established in-house algorithms to estimate system inertia from large frequency excursions using WAMS data. Both these methods have limitations for accurate estimation and continuous monitoring.

GCCIA is planning to initiate the project to monitor and estimate system effective inertia from small frequency excursions using power injection and rate of change of frequency (RoCoF) measurement from PMU data. Half second window will be used to measure the RoCoF following the event of frequency excursion. Clean frequency excursion events caused by known sources are essential to align the RoCoF window with calculations. Therefore, GCCIA will use its BtB HVDC converters to periodically inject power in either direction to create a controlled event of frequency excursion with start time being GPS time stamped.

The measured RoCoF for the same event might be different at different locations based on the location of PMUs as a weak system with low local inertia will cause higher RoCoF. It will be possible for GCCIA to estimate and monitor accurate inertia for each Member State of the GCC Region.

6.3.10. GCCIA: Cross-Border Ancillary Services for intermittency & generation-demand balance

The increased penetration of RES across the GCC interconnected system with increased variability is causing higher unscheduled deviations in power flows on the radial links of the Interconnector impacting both security and economic aspects. These deviations, once controlled and channelize through ancillary services mechanism, will help the Member States to meet their RES targets in a secure way. The process requires technical procedures and regulatory framework for establishing ancillary services market.

GCCIA is developing a mechanism under the cross-border ancillary services to formalize the cross-border unscheduled deviations and the exchange of secondary reserves between the GCC Member States.

GCCIA will start the pilot project in early 2024 with two products, one will cover the fluctuations through the exchange of fast frequency response through BESS, the BtB HVDC between 50 & 60Hz blocks as well as interruptible loads.

The second product of exchanging upward & downward secondary reserves between the Member States to cover generation-demand imbalances caused by the requirements for must-run conventional plants to maintain the area wise required inertia and short-circuit levels.

6.3.11. ONS: Inertia Estimation from active distribution networks

ONS aims to enhance its current system by incorporating inertia calculation using PMUs (Phasor Measurement Units). This addition is designed to complement the inertia values already calculated through SCADA. By comparing inertia figures derived from both SCADA and PMU measurements, ONS can effectively identify any discrepancies. This comparative analysis will enable ONS to estimate the contribution of inertia more accurately, including, for example, the impact of the distribution networks (e.g. rooftop generation) in the system inertia.

7. Report about GO15 surveys

During 2023 GO15 members have been submitted two surveys, on *System Inertia* and *Stability*, respectively with the aim of understanding the main challenges being addressed by TSOs around the world. This section provides a critical summary of the surveys, with the aim to relate about status of system inertia and stability detected by all the participants.

The survey focused on detecting, first of all, vulnerability of the various TSOs, thereafter availability of tools and methods for estimating and observation those phenomena, availability of operating procedures related to mitigation measures and lastly, research and development initiatives for future implementations.

7.1. Survey on System Inertia

The survey on system inertia comprised eleven questions, answered by nine TSOs representatives. The responses indicate that low inertia is not an immediate concern for almost all the interviewees, except in cases where it becomes a critical aspect during contingencies related to significant generation outages. However, nearly all the interviewees express the belief that low inertia will emerge as a critical issue in the next decade due to the widespread integration of power electronic converter interfaced resources.

The significance of inertia in modern power systems is underscored by the fact that all the interviewed TSOs already have at least one tool for inertia monitoring, estimation, and forecasting. Nonetheless, only TERNA (Italy) declares the implementation of mitigation actions based on online inertia estimation, applied by the Control Room using Dynamic Security Assessment (DSA) and Wide Area Measurement Systems (WAMS) information.

Looking ahead, some TSOs are exploring the possibility of introducing innovative ancillary services based on inertia and making modifications to primary frequency reserve policies. Conversely, the majority are working on real-time inertia estimation tools, fast frequency response (FFR) services, and the installation of Synchronous Condensers or flywheels to strategically mitigate the phenomena induced by low inertia operation.

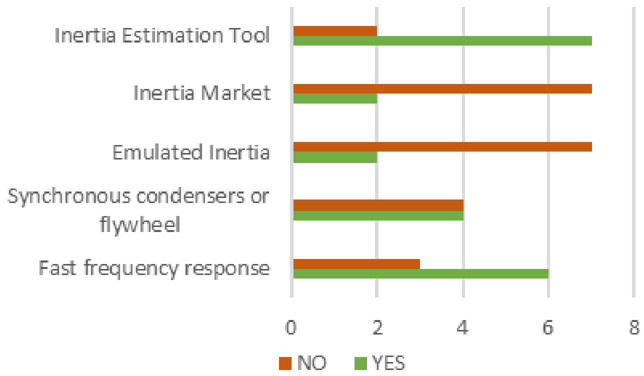

Figure 22 - Mitigating technologies to be implemented

While some TSOs face no particular difficulties introducing certain elements into the system, others grapple with issues related to the correct tuning of parameters and ensuring a proper match between mathematical models and real-world behavior.

Many TSOs have established a minimum threshold for system inertia: ENTSO-E defines a recommended value for the Rate of Change of Frequency (RoCoF), while in other countries current estimate for minimum inertia and minimum RoCoF is compared whit the penetration level of inverter-based generators.

Numerous research and development initiatives are focused on this topic, the most relevant related to estimating inertia using Phasor Measurement Units (PMUs) and implementation of Grid Forming control strategies for inverter-based resources.

7.2. Survey on System Stability

The survey campaign on system Stability has been conducted with the intention of identify which class of instability GO15 members' system is affected, which kind of instability is more dangerous for their network, in which way they monitor system strength and what are the short term and long-term countermeasures to be implemented.

All the interviewees pointed out stability issues in their grids, mainly rotor angle and voltage stability. All classes of stability (Figure 23) are monitored: the most of TSOs monitor classical classes of stability, while in some cases also Resonance stability is considered. Regarding Converter Driven stability, anyone of the interviewed seems to be monitoring it.

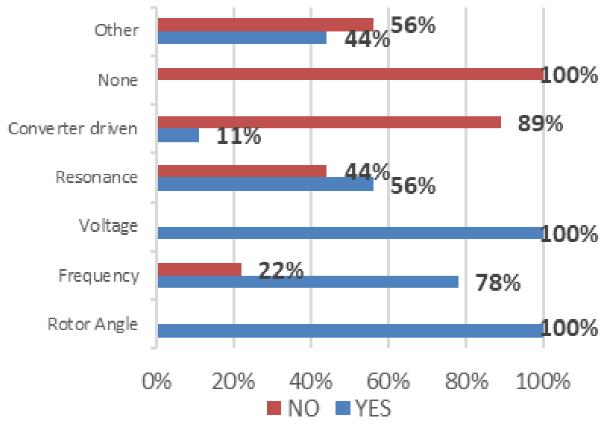

Figure 23 - Class of Instability monitored

Stability issues, impact negatively on the quality of service and reliability of power system and enlarge the risk of serious damage to grid assets. For each one of the previous mentioned types of stability there are established standards to respect based on Grid Code or Transmission Code and manuals for transmission and operation criteria according to field experience.

Even system Inertia and Short Circuit is evaluated as a measure of system strength. The importance of evaluating system strength is underlined by the fact that almost all of the participants monitor system inertia and calculate short circuit. Some TSOs use the RoCoF as a measure of system strength, while others use information coming by field collected through WAMS for real-time evaluation, or based on the number of online components while others estimate inertia and short circuit ratio offline.

Stability for GO15's TSOs is assessed from long term to real time operations, passing through short term. Stability for real-time operations is assessed through measurement-based oscillations, DSA and real-time WAMS-based modal analysis and time domain simulations. For mid-term and long-term stability is evaluated by using forecasting algorithm properly designed for the application, by defining network reinforcements and by the installation of countermeasures like synchronous condensers, braking resistances and series capacitors in order to evaluate the maximum admissible flows. Other long-term improvement related to the growth of inverter-based resources which lead to stability issue are the empowerment of the Defence System and the introduction of regulating capabilities by inverter-based resources.

Another aspect on which the focus is on is the observation of the different classes of oscillations. Almost every interviewee declares to monitor Inter-Area oscillations proving the importance of observing low frequency oscillations modes. Intra-Area and Local Oscillations are still observed from a high number of TSO. Monitoring of Inter-Area, Intra-Area, Local and Plant oscillation modes is made by TSOs by using Wide Area Monitoring Systems which collect measurements from PMUs deployed throughout the network. PMUs are used for several applications, mainly stability analysis purposes through measurement coming from lines, HVDC converter stations, load centres and generation units. Their optimal placement allows TSOs to reach a good coverage of power system in order to observe both inter-area oscillations and local modes.

8. Conclusions and recommendations

This paper presents a comprehensive classification of the main phenomena influencing power system stability, examining research directions and promising technologies and methodologies for improving dynamic grid performance in the presence of large-scale adoption of distributed power converter-based generators. The concept of power system stability is re-examined, taking into account the potential effects arising from the large-scale replacement of conventional synchronous generators by distributed generation systems based on renewable energy sources. Particular attention is paid to critical issues facing modern power systems, including decreasing inertia and vulnerability to dynamic disturbances on multiple time scales, and their potential impacts on the stability, flexibility, and resilience of power systems. Finally, the paper provides a detailed analysis of the most promising enabling technologies for improving system stability.

The significant penetration of converter interface generators (CIGs) requires substantial revisions to conventional policies governing the planning, operation and regulation of power systems [65]. Several countries have witnessed the negative effects of the rapid growth of CIGs connected to the grid, underlining the importance of defining and implementing corrective actions to improve grid flexibility and mitigate the impact on power system stability and security.

In the light of these factors, and of Grid India past report [70], the GO15 Task Force ‘’inertia&stability’’ makes few recommendations at three levels: policy and planning, regulatory and technical.

Policy and planning level

1. System inertia to be considered as a critical parameter in planning and operation of the future transmission grid with high penetration of non-synchronous generating resources.

2. Policy initiatives to encourage deployment of synchronous inertia sources, such as synchronous condenser, and hydro generation, besides provisions for synthetic inertia to be provided by non-synchronous resources, for ensuring adequacy of system inertia.

3. Transnational synchronous interconnections leading to a larger footprint would help in increasing system inertia.

4. In a net-zero scenario envisaged by 2050, generation technologies such hydro (including pumped hydro), nuclear, biomass, green hydrogen fired gas turbines, and thermal generation with carbon capture & sequestration need to be kept on the radar in view of inertia requirements.

Regulatory level

5. Technical definitions of system inertia and associated terms to be incorporated in the regulations.
6. Suitable regulatory provisions need to be evolved to harness potential inertial and fast frequency response (FFR) from Renewable Energy sources, other inverter-based resources, including battery energy storage systems.

7. Suitable regulatory provisions and mechanisms to encourage frequency response from demand side resources, including behind-the-meter generation.

Technical level

8. Tools for Inertia estimation, online measurement and forecasting need to be explored.

9. The time window for rate of change of frequency (RoCoF) measurement and RoCoF limits for various protection schemes to be standardized.

10. The Rate of change of frequency (RoCoF), frequency nadir based under frequency load shedding schemes and over frequency settings in the grid need to be revisited periodically.

11. Studies may be initiated to assess the minimum inertia requirement for secure and stable operation of the transmission grid in an interconnected region under different operating scenarios.

12. Control area frequency response measurement and performance evaluation for frequency events to be strengthened.

13. Synchronous inertia requirements could be considered as one of the constraints in the future Security constrained unit commitment scheme.

Abbreviations and Acronyms

- APG Active Power Gradient
- ARMAX AutoRegressive Moving Average models with eXogenous
- ASD Angle Small Disturbance
- BESS Battery Energy Storage System
- BtB Back To Back
- CCS Carbon Capture and Storage
- CIG Converter Interfaced Generator
- COI Center Of Inertia
- DSA Dynamic Security Assessment
- DSM Distributed System Management
- DT Digital Twin
- ENTSO-E European Network of Transmission System Operators Electricity
- EMS Energy Management System
- FACTS Flexible Alternating Current Transmission System
- FER Flexible Energy Resource
- FRC Frequency Response Characteristics
- GPS Global Positioning System
- HILP High Impact Low Probability
- HPC High Performance Computing
- HVDC High Voltage Direct Current
- ICT Information and Communication Technology
- IEA International Energy Agency
- LFO Low Frequency Oscillation
- LTVS Long Term Voltage Stability
- OLTC On Load Tap Changer
- PDC Phasor Data Concentrator
- PFC Primary Frequency Control
- PMU Phasor Measurement Unit
- POD Power Oscillations Damping
- PSS Power System Stabilizer
- RoCoF Rate of Change of Frequency
- RE Renewable Energy
- RES Renewable Energy Source
- RPG Renewable Power Generator
- SC Synchronous Compensator
- SCADA Supervisory Control and Data Acquisition
- SG Synchronous Generator
- SVC Static Var Controller
- STATCOM Synchronous Static Compensator
- TSO Transmission System Operator
- TYNDP Ten Year Network Development Plan
- UN United Nations
- WADC Wide Area Damping Controller
- WAMPAC Wide Area Monitoring Protection And Control
- WAMS Wide Area Measurement System

- WAPS Wide Area Protection System

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