Technical Report

Future of the Grid: Strengthening ASEAN's Grid Power Quality by Harnessing Stability with DERs and Synchrophasors

ASEAN Centre for Energy

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Soemantri Brodjonegoro II Building, 6th fl.,
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Jl. HR. Rasuna Said Block X-2, Kav. 07-08
Jakarta 12950 Indonesia
Tel: (62-21) 527 9332 | Fax: (62-21) 527 9350
aseanenergy.org

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This study has benefitted from discussions with the representatives from ASEAN power utilities who participated in this *Community of Practice (CoP) for ASEAN Power System Operators.* These discussions took place during the *ASEAN Grid System Operators Convention (AGSOC) 2024* held in Kuala Lumpur, Malaysia, on 14-15 May 2024, and the *9th ASEAN Power System Operators Workshop,* held in Manila, Philippines on 27-29 August 2024. This workshop was the successor of the CoP program for Southeast Asia Grid System Operators, conducted on 23 April 2024, titled *the Role of Transmission System Operators for Successful Multilateral Energy Trading Under the Lao PDR – Thailand – Malaysia – Singapore (LTMS) Project*.

The authors would like to extend their gratitude to the ASEAN Power System Operator (APSO) Secretariat and Heads of ASEAN Power Utilities/Authorities (HAPUA) Working Group 5 (HWG-5) for their guidance, continuous support and collaboration in ensuring the success of the CoP series for APSO members. This report aimed to summarise the key findings from these CoP events to provide valuable insights for the APSO members.

List of Acronyms and Abbreviations

AAS	Auxiliary Agreement Service
AC	Alternating Current
ACE	ASEAN Centre for Energy
ADCs	Analog-to-digital Converters
AGSOC	ASEAN Grid System Operators Convention
AMS	ASEAN Member States
APAEC	ASEAN Plan of Action for Energy Corporation
APG	ASEAN Power Grid
APSO	ASEAN Power System Operators
BESS	Battery Energy Storage Systems
DC	Direct Current
DER	Distributed Energy Resource
DLSE	Distribution Linear State Estimation
DSP	Digital Signal Processors
EGAT	Electricity Generation Authority of Thailand
FLISR	Fault Location, Isolation, and Service Restoration
FPGAs	Field-programmable Gate
GSO	Grid System Operator
GW	GigaWatt
GWh	GigaWatt-hour
GWs	GigaWatt-second
HAPUA	ASEAN Power Utilities/Authorities
HWG-5	HAPUA Working Group 5
HVRT	Voltage Ride Through
IBRs	Inverter-Based Resource
kW	kiloWatt
kWh	kiloWatt-hour
LVRT	Low Voltage Ride Through
MAS	Management and Automation System
MW	MegaWatt
MWh	MegaWatt-hour
MW•s	MegaWatt-second
NAS	Network Attached Storage
NSPs	Network Service Providers
PMUs	Phasor Measurement Units
PV	Photovoltaics
POI	Point of Interconnection
RES	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
RTUs	Remote Terminal Units
SRAS	Secondary Reserve Ancillary Service
TNB	Tenaga Nasional Berhad

TRAS	Tertiary Reserve Ancillary Services
UTC	Universal Time Coordinated
WAMPAC	Wide-Area Monitoring, Protection, and Control
WAMS	Wide-Area Monitoring System

Executive Summary

In recent years, the ASEAN's power grid landscape is evolving. The integration of Distributed Energy Resources (DERs), such as rooftop solar photovoltaics (PV) systems and battery energy storage, is reshaping ASEAN's power systems by increasing flexibility and resilience. Despite the region's abundant renewable energy resources like solar and wind, the adoption of DERs remains largely untapped. The 8th ASEAN Energy Outlook (AEO8) highlights that Indonesia, Malaysia and Viet Nam have significant solar potential, with Indonesia alone capable of 194 GW to 655 GW, yet as of 2023, only 140 MW had been installed which falling short of its 2025 target of 3.6 GW. While policy measures such as feed-in tariffs have supported adoption, barriers such as low net-metering rates, high costs and regulatory hurdles continue to slow progress.

Power quality is a critical factor in power system stability, influenced by frequency, voltage, and harmonics. The stability of these parameters is essential for maintaining reliable energy supply. However, ASEAN Member States (AMS) face distinct challenges in integrating DERs into the grid. Viet Nam, with its high share of variable renewable energy, struggles with transmission congestion, forecast errors, and low system inertia. Thailand deals with major line tripping and generation trips, while Lao PDR, heavily dependent on hydropower, must manage seasonal fluctuations between surplus and shortages.

To mitigate these risks, advanced power system monitoring and control solutions must be adopted. Technologies such as synchrophasors and phasor measurement units (PMUs) offer real-time visibility of grid conditions, enabling faster detection and response to disturbances. Wide-Area Monitoring, Protection, and Control (WAMPAC) systems further enhance grid resilience by enabling predictive analytics and automated corrective actions. These innovations, combined with enhanced regulatory frameworks and digital grid modernisation which will be a key to future-proofing ASEAN's power systems to ensure a stable, efficient, and high-quality electricity supply.

Preamble

The G-PST Consortium is a worldwide community that acts as a force multiplier in the global effort to drive a rapid transition to a zero-carbon electricity grid, connecting its ecosystem partners and creating intentional, inclusive, and purpose-driven collaboration to solve common challenges. A core objective of G-PST is to facilitate a knowledge-sharing platform through a CoP, by partnering with emerging economies and developing regions for system operators, including Africa, Latin America, and Southeast Asia. Building on the success of the first Southeast Asia CoP held in November 2022, ACE in partnership with NREL under the G-PST Consortium, is conducting a series of CoP to facilitate a participants-driven activity for knowledge and hands-on experiences sharing in the pursuit of accelerating the transformation to low-emission power system for the ASEAN power system operators under the HAPUA. The key outcomes from these discussions will be documented in technical reports, white papers, and other knowledge-sharing platforms to ensure broader accessibility and impact.

As part of ACE-NREL partnership, in collaboration with the GSO of Tenaga Nasional Berhad (TNB) and APSO under HAPUA WG-5, ACE conducted a workshop on the ASEAN Grid System Operators Convention 2024 on 14-15 May 2024 in Kuala Lumpur Malaysia, inviting system operators from all AMS and global experts to share their insights on two critical themes of *Power System Stability and Power Quality with Increasing Inverter-based Resources and Synchrophasor-based Power System Analytics and Defense*. The discussion focused on common power quality challenges, best practices for power system operation, and advanced monitoring technologies such as synchrophasor-based analytics to provide in-depth knowledge sharing amongst system operators.

Further reinforcing this initiative, ACE, in collaboration with USAID's Southeast Asia Smart Power Program (USAID SPP) and G-PST NREL, supported by HAPUA WG-5 in conducting the 9th APSO Workshop from 27–29 August 2024 in Manila, Philippines. These discussions formed the foundation for this technical report, titled *Future of the Grid: Strengthening ASEAN's Grid Power Quality by Harnessing Stability with DERs and Synchrophasors* developed as part of ACE-NREL partnership deliverables aims to provide ASEAN's system operators with a comprehensive understanding of power quality challenges in an evolving grid landscape, particularly as Inverter-Based Resources (IBRs) become a dominant part of the generation mix. The report serves as a strategic resource to strengthen ASEAN's grid reliability, power quality management, and operational resilience for the region.

Introduction

The ASEAN region's renewable energy integration into the electricity grid – has historically shown resilience amidst the COVID-19 pandemic. Data indicates a notable rise in installed capacity for Variable Renewable Energy (RE) sources such as solar and wind power plants representing a shift towards a sustainable future and enhanced energy security. This trend is particularly evident in Viet Nam (42.5% growth), Cambodia (13.1% growth), and Singapore (21.2% growth in solar PV alone). While this signifies a positive shift towards RE implementation, further investigation is needed to understand the imminent effect of high VRE integration.

The development of power systems is shifting towards the utilisation of Renewable Energy Sources (RES). There are two approaches to integrating higher renewable energy into the grid, a centralised approach (utility-scale PV and wind power plant) and a decentralised one (distributed energy resources/ DERs). DERs allow electricity consumers to shift their role to producing consumers/ *prosumers*, posing both challenges and opportunities for the grid. In both ways, the power system utilities will inevitably face challenges in terms of operating the grid.

RES generation commonly employs inverters to convert Direct Current (DC) voltage into Alternating Current (AC) voltage. Unlike synchronous generators, the integration of IBRs as a distributed generator (DG) may cause system instability and affect power quality during a loss of electricity demand/generation or faults in the power system operation, due to the absence of mechanical inertia. Reverse power flows, power quality issues, and variability of load and supply would disrupt the previously "predictable" electrical landscape.

To inform interested stakeholders, this guide addresses a variety of questions about possible solutions to integrate a higher proportion of renewables into the grid through Distributed Energy Resources (DERs), and it describes the challenges of adaptions in grid protection and control systems to accommodate the unique properties of IBRs. Include the guiding questions in the chapters of the report:

- How Will DERs Shape ASEAN's Power System?
- What is Power Quality (PQ) and How do we Determine the Quality of Power?
- What are the PQ Issues in ASEAN?
- How do International Best Practices Mitigate PQ Issues?
- What is Synchrophasor and Why is it Important in the IBRs?
- What's Next in Strengthening the ASEAN's power system?

How Will DERs Shape ASEAN's Power System?

1.1 Aggregated DERs

United States Federal Energy Regulatory Commission in its 2018 report defined Distributed Energy Resources as a source of power located in the distribution system. Rooftop solar PV (distributed generation), electric and thermal storage, energy efficiency equipment, and electric vehicles are included as distributed energy resources in the report. In the United States, DERs become more known due to the issuance of FERC Order No. 2222 in 2020 with the main goal of enabling distributed energy resources to participate in the wholesale electricity markets. The order allows DERs (including retail consumers) to participate in the wholesale electricity market, creating a competitive environment in the electricity supply business.

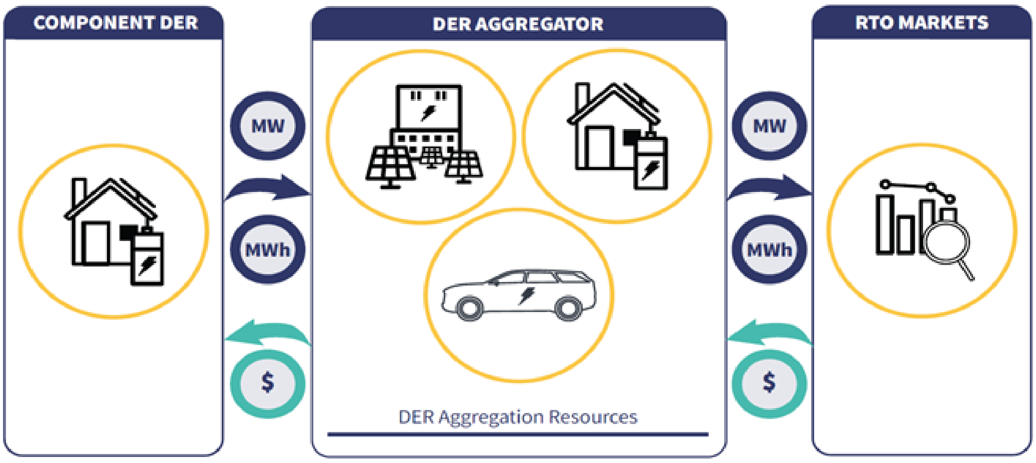


Figure 1 Illustration of DERs Participation in the Wholesale Market [1]

Although DERs are allowed to participate in the wholesale market, their relatively small capacity may be widely dispersed and would be difficult to compete with the conventional power suppliers in the market. Given the condition, the DERs would often be bundled together to be sufficient size for market participation, hence the name "Aggregated DERs" commonly referred to as "Virtual Power Plants/ VPPs". The aggregated DERs would then directly participate in the wholesale market via an aggregator and the compensation made from the market would be shared with the DER owners in return, as electricity cost reductions and up-front incentives for using DERs [2]. Besides cost-related benefits, participating in the wholesale market as aggregated DERs would play a role in reducing fossil fuel reliance and, to some extent, enhancing power quality through the reduction of distribution losses.

The growth of DERs indicates technological growth and innovation. From Vehicle-to-Grid (V2G) to hybrid solar PV system, the implementation of technological innovations is being shown by the increase of DERs and the growing size of DERs market. A news release from Wood Mackenzie reported that the United States is expecting a doubling in its capacity from 2022 to 2027, reaching 262 GW of additional DER from 2023 to 2027 [3]. This is mainly due to the incentives given on electric vehicles, renewable energy projects, and demand flexibility technologies from the Inflation Reduction Act

(IRA) and the National Electric Vehicle Infrastructure grant program, influencing the growth of innovation in EV technologies and flexible resources. The following section will outline the impact of the growth in DER to the power grid.

How do Aggregated DERs Impact the Grid?

DERs encompass a broad range of technologies that support decentralised electricity generation and storage. According to the North American Electric Reliability Corporation (NERC), DERs can be categorised into six main types, each serving distinct functions within the power system:

- **Distributed Generation (DG):** electricity generation unit(s) which are owned and operated by distribution or retailers
- **Behind-The-Meter Generation (BMTG):** electricity generation unit(s) at a single location on the customer's side of the retail meter that serve all or part of the customer's retail load with electric energy.
- **Energy Storage Facility (ES):** energy storage device or multiple devices at a single location, on either utility side or the customer's side of the retail meter.
- **DER Aggregation (DERA):** virtual resources formed by compiling multiple DERs as a single source at its "virtual" point of interconnection.
- **Micro-Grid (MG):** Aggregation of multiple DER types behind the customer meter at a single point of interconnection that has capability to island.
- **Cogeneration:** Production of electricity from steam, heat, or other forms of energy produced as a by-product of another process.
- **Emergency, Stand-by, or Back-up Generation (BUG):** Generation unit that serves in times of emergency at locations and by providing the customer or distribution system needs.

Each type of DERs exhibits distinct operational characteristics in supplying electricity to the grid. However, despite these differences, DERs generally influence the technical, socio-economic, and environmental dimensions of the power system in similar ways, shaping grid stability, market dynamics, and sustainability outcomes.

Distributed generation would pose some disruptions in the distribution network operations. From a conventional unidirectional flow (generation – distribution - consumers) to a bidirectional flow (the increase of prosumers, where the consumers would also produce electricity to be exported to the grid), changes in the power flow could potentially impose an effect on the quality of power distributed through the power grid.

With the rise of interconnections and grid enhancements worldwide, grid losses posed as one of the main challenges to be addressed. In theory, distribution network losses heavily correlate with the amount of current that runs through a conductor. The lower the voltage level, the bulk power being transferred becomes inefficiently transmitted to the consumers through the conductor. The impedance of the conductor also plays a role in determining the efficiency of the distributed power. As the distribution line becomes longer, the dissipated power becomes higher due to the increase in the total impedance. That's the reason why a co-located solar power plant, rooftop solar PV for instance, would decrease the level of distribution grid losses due to the relatively close distance from the generation unit to the load. The power injection from distributed generation would decrease the system losses until it exceeds the connected load capacity. Exceeding power injection would create reverse power flow to the radial systems, which would then influence system losses to grow throughout the system [4].

Reactive power regulation/ compensation in the distribution network has the potential to improve the economy of distribution network operation, ensure safe and reliable operation, and improve voltage fluctuation and network loss. Most of the novel solar inverters have the capability to output reactive power into the grid, which may affect the reactive power regulation of the connected distribution network. Coordinated P-Q control from distributed generation units by changing voltage amplitude and phase could be a way to provide reactive power compensation into the grid, thus creating a node voltage regulation mechanism through balancing P-Q output [5].

Reactive power (Q) injection into the grid would influence the voltage regulation mechanism of the system. The changes in line-to-line voltage magnitude are parallel with the changing reactive power injection, according to the reactive power transfer equation [6]. Thus, distributed generation from renewable energy sources with reactive power control would benefit the grid in tackling voltage drops. Although it may present benefits in terms of reactive power regulation, higher penetration of DGs into the distribution grid would disrupt the voltage level to become overexcited, which could also trigger overvoltage tripping from the protection equipment.

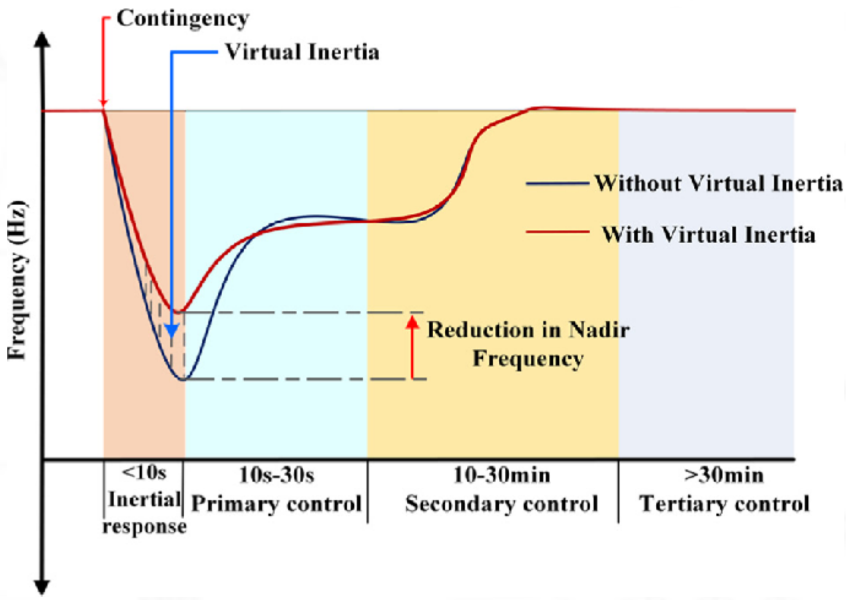


Figure 2 The Effect of Inertia in Contingency Event

Other than voltage stability, DERs also present an impact on the frequency stability of the connected system. Due to the lack of rotating mass in the power electronic equipment of the DGs, the reduced inertial momentum of the system could potentially cause load shedding even in the case of small disturbances. The rate of change of frequency (ROCOF) increases as the system inertia decreases, making the slope of the frequency drop steeper and the nadir frequency lower upon a contingency case occurring [7]. Figure 2 illustrates the importance of inertia and introduces the term "Virtual Inertia" as the solution to the diminishing rotating mass in recent years [8]. According to Virtual inertia is a form of a fast-response power system control mechanism, which combines a control algorithm, energy storage, and power electronics, that could replicate the characteristics of rotating mass, by dispatching active power into the system within a fraction of a second [9]. The main requirement of a virtual inertia system is that it must operate at a very short time interval and autonomously, with the purpose of enhancing system stability and enabling greater penetration of renewable energy sources (RESs).

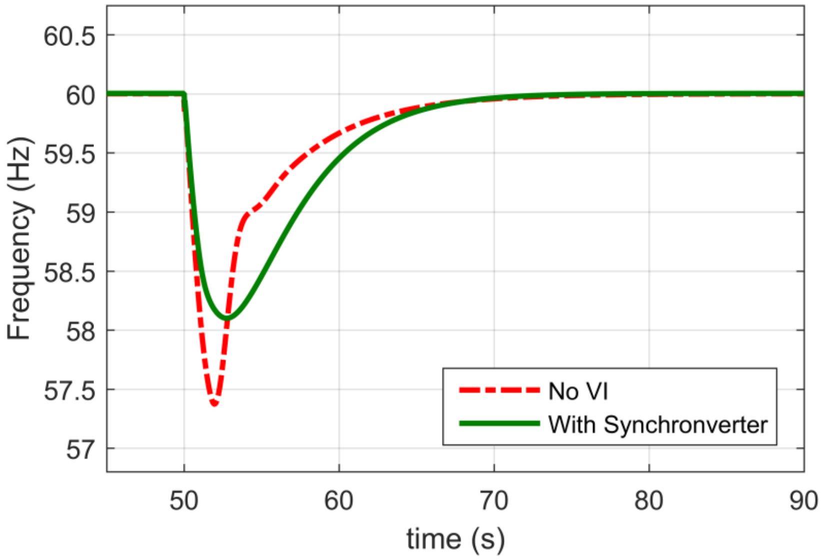


Figure 3 Lab Simulation of Synchronverter Implementation on Frequency Drop [9]

Given the mentioned features of DERs in providing virtual inertia, centralised control of aggregated DER would be sufficient to provide a supporting rotating mass for the system's stability. This virtual inertia would dampen the ROCOF level, creating a less steep system frequency drop in the case of a generator tripping. Synchronverter (synchronous converter), implements the virtual inertia mechanism using power electronics. Through lab simulations, the use of a virtual inertia mechanism would create a damping effect on frequency dip, making the drop in frequency less severe and lowering the chance of cascading trips among the power system equipment. The mechanism also presents a smoother frequency recovery due to the drop of ROCOF that makes the recovery time a fraction of a second slower.

How is the Development of DERs in ASEAN?

The development of DERs in ASEAN has gained momentum as countries seek to enhance energy security and grid flexibility. Indonesia, with its vast renewable energy potential, exemplifies this trend. As an archipelagic nation, it has identified up to 20 GW of technical potential from marine energy sources such as tidal, wave, and current energy. A notable example is the Larantuka Adonara site in eastern Indonesia, which could accommodate 5–20 MW of installed capacity. In addition to marine energy, the country is leveraging rooftop solar PV and battery energy storage systems (BESS) to electrify remote communities and reduce reliance on diesel generators. Currently, 600 MW of hybrid PV and BESS are installed across 367 locations, providing a decentralised energy solution for off-grid areas.

The increasing adoption of electric vehicles (EVs) in Indonesia also presents both challenges and opportunities for the national power system. The surge in EV demand, supported by government incentives, is expected to increase electricity consumption, particularly during peak hours. To mitigate potential grid strain, vehicle-to-grid (V2G) integration is being explored, enabling EV batteries to store energy during off-peak hours and supply electricity back to the grid when demand peaks. To facilitate this, a smart control centre utilising Inter-Control Centre Communications (ICCP) is being developed to integrate DERs and V2G technology within the distribution system operator (DSO) network. However, successful implementation depends on regulatory adjustments, advanced metering infrastructure, and financial incentives, particularly for rooftop PV adoption to support EV charging needs.

As inverter-based renewable energy penetration increases across ASEAN, ensuring grid stability and power quality remains a pressing issue. Grid-following inverters, which enable automatic voltage control and frequency synchronisation, are recognised as a key solution. However, policy and financial challenges continue to affect deployment across AMS. Indonesia is addressing this through efforts to update its grid code to facilitate larger VRE integration, while Vietnam is working to establish regulations that standardise grid-following inverters and reduce costs for system operators.

The integration of DERs also introduces new operational challenges, particularly in balancing energy supply and demand. Higher penetration of IBRs and the increasing role of prosumers in energy markets are reshaping traditional electricity consumption patterns, leading to voltage stability issues and harmonics disturbances. Addressing these technical challenges will require comprehensive regulatory frameworks, investments in smart grid technologies, and enhanced grid monitoring capabilities. The next section will examine specific power quality concerns associated with DER deployment and strategies for ensuring a stable and resilient power grid in ASEAN.

How do we Determine PQ?

Power quality is defined as the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment [10]. Ensuring the quality of distributed power through effective power quality control is critical for the smooth functioning of sensitive equipment, as it will save downtime and maintenance costs. It also contributes significantly to overall system efficiency and dependability, hence promoting the best performance of both industrial and consumer electrical devices. The three following key parameters are usually considered in determining the quality of distributed power, which are frequency, voltage, and harmonics.

4.1 Frequency

System frequency is the measure of alternating current oscillations per one-second basis in a wide-area synchronous network. Most AMS use 50 Hz (excluding the Philippines, which uses 60 Hz) as the system frequency standard with an allowed deviation of ± 0.2 Hz. Deviation in the frequency tends to happen in a power system. It is mainly due to the imbalance between the generated power from the power plants and the absorbed power from the load. Sudden changes in power generation due to disturbances that led to the tripping of the generator unit and line faults caused by external factors are some of the reasons why frequency deviations might occur.

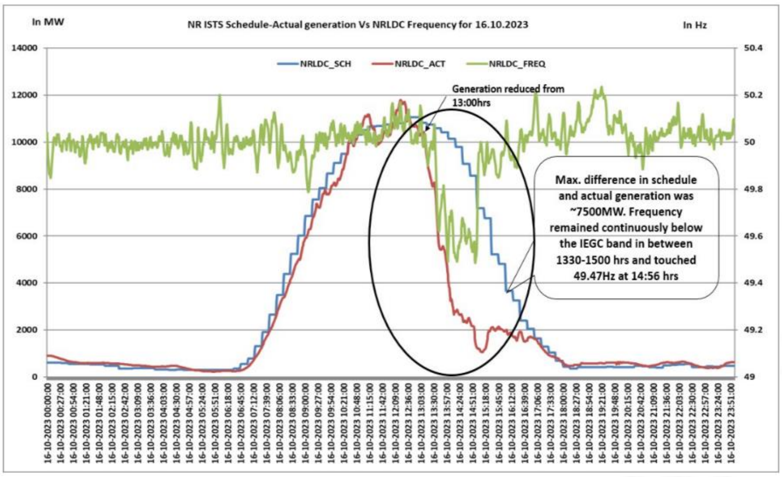


Figure 4 Impact of Cloud-Shading on Solar Power Generation and System Frequency in October 2023 [10]

In the case of VRE integration into the grid, the intermittent characteristics of VRE may bring obstacles in maintaining the stability of the system frequency and overall power quality. Looking at the case of Grid India as shown in Figure 4, a sudden cloud-shading of the solar power plants would cause a reduction of 7,000 MW in generated power. The sudden drop then led to a drop in frequency, reaching a critical low of 49.48 Hz for over one hour. A huge decrease in frequency as mentioned in the case above would impact the power systems equipment, such as motors and transformers, as low frequency would cause lower rotational speed of the motor, lowering the back EMF (voltage) that the motor is using. The lower the voltage, the higher the current drawn to keep the motor operational, hence would cause heating in the power system equipment, de-rating the insulation, and decreasing the lifetime.

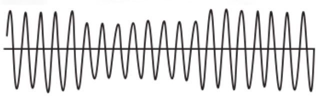
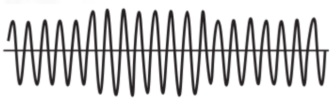
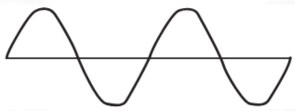
What is the significance of inertia to the system's frequency?

Inertia, stored energy in the form of a total rotating mass of a synchronous network, is an important parameter that is important to maintain system stability in the case of a generation tripping event. In the case of high renewable energy penetration into the grid, the system inertia tends to decrease proportionally due to the IBRs being a static generation unit, rather than a rotating unit like synchronous generators. Theoretically speaking, the decrease of inertia in the system would lead to an increase in the rate of change of frequency (ROCOF), which consequently leads to a higher loss of generation when a system fault occurs. However, the system inertia and ROCOF depend mostly on the clusters of grids that the renewable resources are connected to and whether the system has enough synchronous machines to cover sufficient inertia decrease or not. Hence, the reduction of inertia should be complemented by a fast-response governor or control unit to accommodate faster frequency change clearance time.

4.2 Voltage

Voltage levels amongst the ASEAN Member States vary from one country to another as imprinted on the country's grid code and technical standards. For instance, Indonesia uses 500 kV, 275 kV, 150 kV, and 70 kV for its transmission level, while Thailand uses 500 kV, 230 kV, and 115 kV, with most countries allowing +5% and -10% deviation on their transmission voltage. Distortion in voltage arises because of sudden or persistent electrical disturbances. Lightning strikes, engine starting and stopping, fault clearance, and other harmonic-generating occurrences are examples of transient disturbances [10].

Table 1 Types of Voltage Disturbances

Disturbance type	Description	Causes
Sag 	Low voltage (often < 80%) for multiple periods.	Starting heavy load, utility switching, ground fault
Swell 	High voltage (often >110%) for multiple periods.	Load reduction, utility switching
Waveform distortion 	Deviation from ideal sinewave due to the presence of harmonics or interharmonics.	Rectifiers, phase-angle controllers, and other nonlinear or intermittent loads.

The stability of system voltage is heavily influenced by the amount of reactive power in the system; busbars/ terminals absorb reactive power (Q) to maintain voltage stability. Maintaining voltage stability through reactive power could be compensated by series and shunt compensation such as capacitor banks and reactors, although dedicated investments for the compensators are needed. Recent inverter technologies have advanced control of the generated power, allowing reactive power generation through switching mechanisms of power electronics (using freewheeling diodes). Given the importance of sufficient reactive power supply in maintaining voltage stability, IBRs should be operated in a fixed power factor mode as a form of reactive power compensation.

4.3 Harmonics

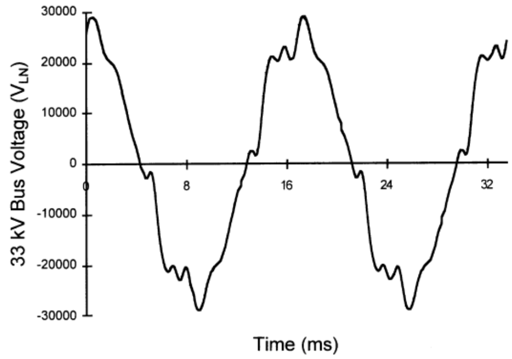


Figure 5 Illustration of Harmonic Distortion on Voltage Waveform [12]

In an era of IBRs-dominated power generation, harmonics become one of the main challenges in power system operation. Harmonics are frequency components that are integer multiples of the fundamental line frequency due to the integration of non-linear loads, such as arc furnaces and inverters. It could be measured by looking into the individual harmonics (per order) and quantified into Total Harmonics Distortion (THD) which totals the amount of harmonics distortion from each harmonics order per fundamental harmonics to better understand how severe the distortion is. IEEE defines the advised voltage and current harmonics distortion criteria in the electrical system design, with a maximum of 1.5% THD in a 500 kV transmission system and 5% THD in a 20 kV distribution system. If the harmonics level exceeds the limits, the system would likely suffer an increase in power losses due to transformer heating, reduction in steady-state power carrying quality and heating in switchgear, and maloperation of protection systems [12].

What are the PQ Issues in ASEAN?

AMS power system comprises various power generation sources and levels of demand, different technical standards (voltage level and frequency), and different levels of interconnectedness within the national grid. Varying grid development phases and recent advancements in distributed generation would bring power quality challenges in the power system operation. Frequency stability is one of the most common power quality issues in ASEAN, and even worldwide, especially in recent years where distributed renewable energy sources are becoming a norm in most countries.

5.1 Lao PDR

Electricity supply in Lao PDR is dominated by hydropower plants, comprising of over 95% of the generation mix. Thermal power plants like coal and gas only take up 2.22% of the generation mix, while solar only 1.62%. The hydro-dominated Lao PDR reserves average active storage of 27% hydropower capacity in the case of drought or ambient temperature increase, as a measure to tackle power supply shortage. Data from Electricite du Laos (EDL) shows that Lao PDR experienced 84 times unplanned outages at the 230 kV transmission system due to external disturbances and operational challenges like stability issues. The frequent tripping costs Lao PDR 3 power blackouts with a total of 83 minutes. Neighbouring countries such as Thailand and Cambodia which are frequent power importers from Lao PDR, would also feel the losses caused by those outages.

As grid operation reinforcement efforts, Lao PDR implemented some mechanisms to ensure the security of supply and power quality. Power Oscillation Monitoring System is applied as a Wide-Area Monitoring System (WAMS) for the Thailand-Lao PDR cross-border interconnection, overseeing the occurred oscillations on both sides of the interconnectors and the results of the damping mechanism on frequency oscillations. Special schemes, including generator and load shedding, are also set up as stability measures against supply and demand imbalance with 6- and 7-step shedding, respectively [13].

5.2 Thailand

Electricity in Thailand has been accessible to almost 100% of the population, influencing rapid growth of electricity demand in the country. According to a report by EGAT in 2020, the country's electricity is mainly generated by thermal power plants, which are dominated by natural gas fuel power plants. Renewable energy accounts for over 19% of the total capacity, with the largest hydropower plant possess an installed capacity of 779.20 MW. In transmitting bulk power, Thailand's transmission system ranges from 69 to 500 kV with a total of 36,478 circuit-kilometers spans within the country, allowing power transfer to almost all area in Thailand [14].

Power system stability issues seldom occur in Thailand's power system, which is mainly caused by major line trips, small-signal stability issues (a small rotor angle disturbance causing an unstable oscillation of the system frequency), and large-generation trips. Thailand's power system operators already mapped out the mitigation methods for each disturbance, which are:

- Major line trips could be mitigated using the generation-shedding scheme, reducing the imbalance in the electricity supply and demand.
- Small-signal stability could be mitigated through a WAMS. The WAMS technology is available at the dispatch centre and could be utilised for monitoring the damping of oscillations in the system.

- Large-generation trips could be mitigated using load-shedding and HVDC stability functions [15]. The HVDC stability functions consists of 4 main sub-functions:
    - Power run-up function to send a signal to increase the HVDC power level to the required power setpoint.
    - Power run back function to send a signal to reduce the HVDC power transfer to the setting power level.
    - Power swing damping function to adjust the power transfer to counter frequency oscillations.
    - Frequency limit control function to adjust the transferred DC power to compensate or decrease the frequency of the system

5.3 Viet Nam

Back in 2020, Viet Nam experienced a *boom* in its solar and wind power installed capacity, reaching an additional capacity of more than 10 GW just in one year and remained consistent in the next two years achieving additional solar and wind capacity of 1.7 GW and 3.4 GW, respectively in 2022. The Viet Nam *RE boom* was caused by the generous amount of national renewable energy incentives through various feed-in tariffs (FITs) on renewable energy projects, accelerating renewable energy development on a national basis. Such incentives create a sudden increase in the national renewable energy generation, achieving 56.88% of the RE share in installed capacity [16]. As expected, the huge increase in renewable energy would cause many powers system operational challenges.

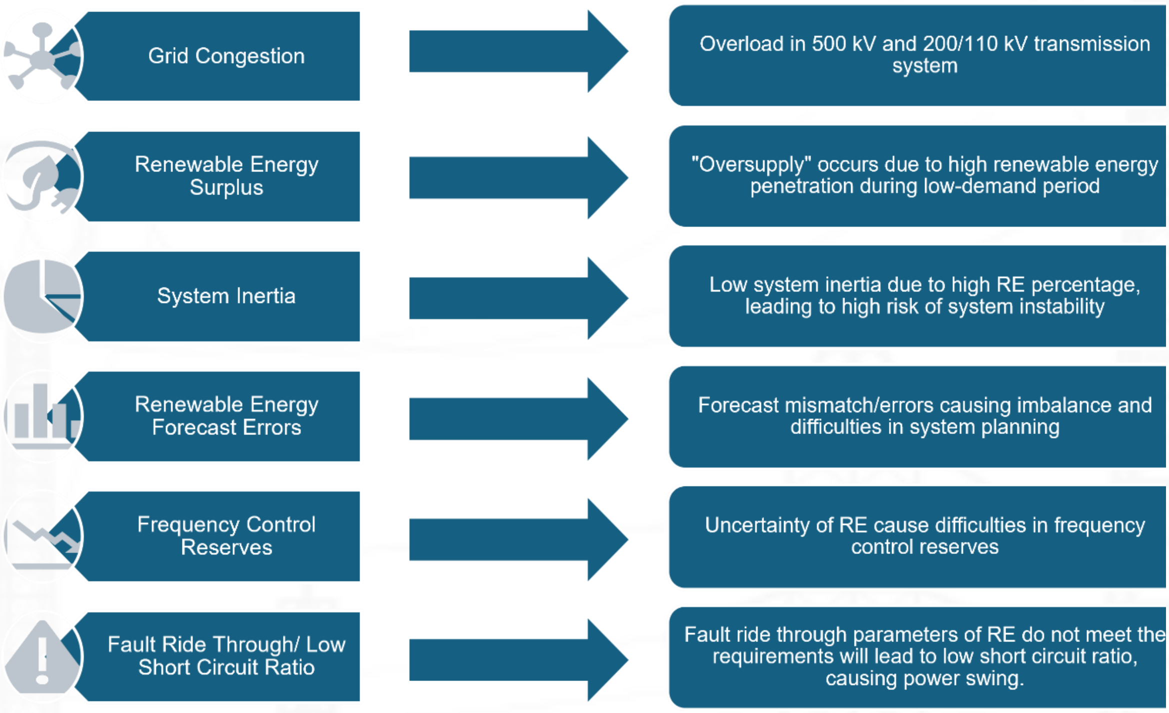


Figure 6 Operational Challenges of High VRE Penetration in Viet Nam's Power System [16]

Regarding stability issues, there are two main power system challenges in Viet Nam caused by the rise of distributed energy resources and variable renewable energy, which are renewable energy forecasts error, system inertia, and frequency control reserves. Inertia provides resistance to frequency drop in the event of a large power plant or transmission failure, holding the rate of change of frequency to remain stable and giving the systems time to respond and rebalance supply & demand. Second, renewable energy forecast errors could cause a mismatch in system planning. Such an issue could potentially cause an imbalance in the supply and demand market, creating an instability of the system's frequency and/or curtailed electricity.

How do International Best Practices Deal with PQ Issues?

6.1 Lesson Learned from International Best Practices

The integration of IBRs into power grids presents significant power quality (PQ) challenges, requiring robust mitigation strategies and advanced fault-clearing measures [18]. Drawing from operational experiences in India's grid, power system operators have identified three key parameters essential for maintaining grid stability and PQ management in high-IBR environments:

6.1.1 Frequency

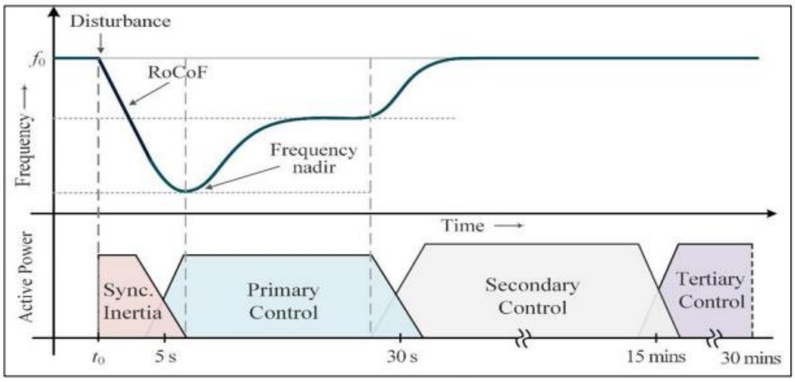


Figure 7 Frequency Response and Control Timeline Following a Disturbance [18]

The aim is to manage the frequency of IBR penetration by addressing factors such as increasing the ROCOF, reducing the nadir frequency, and moderating excessive frequency variations. Primary response, also known as primary frequency control, is an automatic and quick process that is performed immediately following a disruption to stabilise frequency variations caused by supply-demand imbalances. This crucial function usually lasts a few seconds to a few minutes. Following that, the secondary reserve ancillary service, which has a delayed automatic response, adjusts the power output of certain generators to restore the frequency to its nominal value and replenish the primary reserve capacity. Tertiary Reserve Ancillary Services (TRAS) are manually active and try to restore the secondary reserve to its original level by including demand-side response measures and modifications in slower, often less efficient power facilities. TRAS is normally started within 15 minutes following a disruption and can be active for several hours if necessary [18].

Table 2 Frequency Control Ancillary Services Approaches

Reserve	Start of Activation	Full Availability/ Deployment	Ability to Sustain the Full Deployment
Primary Response	Immediately as soon as the frequency crosses dead band	Within 45 sec	5 min
Secondary Reserve Ancillary Service (SRAS)	Within 30 seconds after the receipt of the AGC signal	Within 15 min	30 minutes or till replaced by Tertiary Reserves
TRAS	Within 15 minutes of dispatch instruction from NLDC/RLDC		60 min

The frequency response graph after a disturbance typically displays a first drop from nominal levels (e.g., 50 Hz) due to rapid supply-demand imbalances. This is quickly addressed by the primary response, which restores frequency. The secondary reserve then progressively restores frequency to nominal levels by changing generator outputs, followed by tertiary services that fine-tune and maintain stability over a longer duration of time. This timeline shows the various response times: seconds to minutes for primary, a few minutes for secondary, and up to several hours for tertiary services. This graphical analysis evaluates the effectiveness of several regulatory techniques in maintaining grid stability after disturbances.

What are Nadir and Zenith, in terms of power system frequency?
Frequency nadir means the lowest frequency point that the power system experienced in a period of fault/ disturbance, while zenith means the highest frequency point. The frequency nadir is usually reached when a fault/ disturbance occurs, causing generators to trip and the electricity supply to decrease significantly, thus lowering the frequency. On the other hand, the frequency zenith usually occurs when there is a sudden increase of supplied power or due to an overshoot condition after fault clearance

6.1.2 Voltage

The controlling voltage of IBR penetration involves addressing static reactive power balance, dynamic reactive power balance, and mitigating larger voltage excursions. Here are some strategies employed by the Indian grid to maintain voltage:

6.1.2.1 Avoiding major switching operations

Grid India suggests avoiding major switching operations in large Renewable Energy (RE) complexes after a particular period to maintain system stability and avoid voltage fluctuations. Reactive power control has been changed from voltage control to fixed Power Factor (PF) and fixed Reactive Power (Q) in circumstances when amplification oscillations were seen, stabilising voltage levels and enhancing system performance.

Table 3 Analysis of Plant Behaviour During Oscillations in IBRs PQ Issues

Classification based on plant response	Behavior	Analysis
Category-1: Limited variation of reactive power in phase with voltage.	Non-responsive	A limited reactive power variation is observed from these RE plants as they are operating in constant power factor mode and in fixed Q mode.
Category-2: Large variation of reactive power nearly in phase with voltage.	Detrimental i.e. Aggravating the oscillation	The plants are responding to the variation in pooling station voltage by the action of their voltage controller. The communication delay associated with the plant results in delayed injection of reactive power from RE plants and thereby leads to amplification of voltage oscillation.
Category-3: Large variation of reactive power nearly out of phase with voltage.	Supporting i.e. Damping the oscillation	These plants with high gain and minimum Power Plant Controller (PPC) delay exchange reactive power in response to the grid voltage in phase opposition as per the desired characteristics of the plant voltage controller resulting in damping of voltage oscillation.

Grid India has proposed a categorisation system for renewable energy (RE) plants based on their reactive power responses to fluctuations in voltage. Plants in Category-1 induce little swings in reactive power and operate reliably in constant power factor and fixed Q modes. Plants in Category-2 have significant reactive power fluctuation that is virtually in phase with the voltage, which may worsen voltage oscillations caused by reactive power injection delays. Category-3 plants use reactive power that is considerably out of phase with voltage, effectively minimising voltage fluctuations by responding in opposition to grid voltage phases. To produce this damping effect, these plants utilise high gain and low Power Plant Controller (PPC) delay, as specified in their voltage controller settings.

6.1.2.2 Revision in HVRT and LVRT settings at inverters

Table 4 Revision in HVRT settings at Inverter in coordination with POI

Over Voltage (HVRT) stages at inverter	Over Voltage setting earlier (Default)		Over Voltage setting later (tuned)	
	Voltage (in p.u)	Time (in sec)	Voltage (in p.u)	Time (in sec)
Stage-1	1,1	2	1,15	10
Stage-2	1,2	0,2	1,2	2
Stage-3	1,3	0	1,3	0,2

Grid India suggests adjusting the High Voltage Ride Through (HVRT) and Low Voltage Ride Through (LVRT) settings to guarantee compliance at the Point of Interconnection (POI) for IBRs, as well as maintaining voltage within acceptable ranges during grid disruption. Inverters should also have improved HVRT settings to provide quick responses to voltage variations. Coordinated protection settings for inverters/WTGs are required to survive severe voltage circumstances at the POI, guaranteeing safe operation and grid stability. Furthermore, inverters/WTGs must operate under defined low- and high-voltage circumstances, assisting the grid during disruptions. Compliance with power quality requirements such as harmonics, DC injections, and flickers is needed, as are simulation reports and certificates for PQ compliance.

What is the importance of Fault Ride Through Capabilities in ensuring system stability?

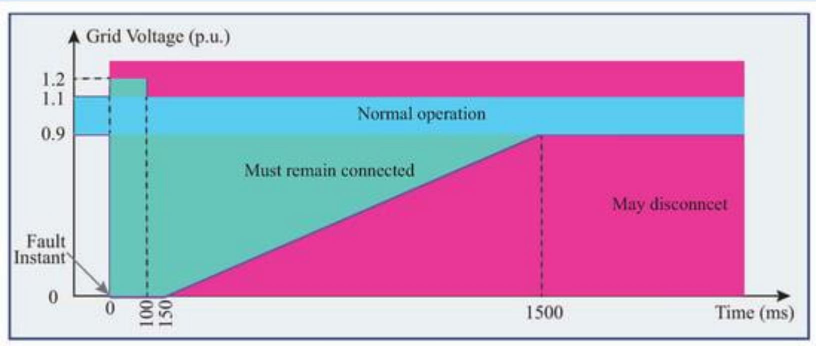


Figure 8 Fault Ride Through Diagram [24]

Fault Ride Through (FRT) capability is defined as the performance of a generation unit, particularly IBRs, to keep its connectivity to the system during and post-fault circumstances. FRT or Low-voltage Ride Through (LVRT) is important in maintaining a continuous supply of electricity to the system, to endure temporary voltage dips which could potentially result in a widespread outage. Grid codes usually state the needed time and voltage of which the generation units need to endure and keep connected, to support the recovery of the system stability.

6.1.3 Harmonics

IBRs must demonstrate their compliance with the technical grid connection criteria, including harmonics fluctuations. This includes producing simulation reports and certificates to comply with CEA standards. Grid India may incorporate harmonic filtering technologies at the point of common coupling (PCC), such as active or passive filters, to decrease distortion and preserve grid quality. Grid India strictly enforces grid codes that establish harmonic distortion limitations to prevent excessive harmonics. Regular monitoring and maintenance of harmonic levels and mitigation devices are required to detect deviations and maintain effective management.

Table 5 International Standards for Harmonics in IBRs PQ Issues

Standard	Description
IEEE 519-2022	IEEE Standard for Harmonic Control in Electric Power Systems
IEEE 2800	IEEE Standard for Interconnection and Interoperability of IBRs Interconnecting with Associated Transmission Electric Power Systems
IEC TR 61000-3-7:2008	Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems
IEC 61000-4-30:2015+AMD1:2021	Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods

6.2 Australia

Australia's approach to PQ assessment in IBR integration is anchored in technical standards and regulatory compliance to maintain grid stability and reliability. The Network Service Provider (NSP), responsible for overseeing power network infrastructure, enforces emission limits on voltage parameters, ensuring that harmonic voltage distortion, voltage fluctuation (flicker), and voltage imbalance remain within acceptable thresholds. A critical aspect of PQ assessment for IBRs in Australia is the emphasis on voltage performance monitoring, which includes continuous evaluation of power quality indicators through real-time measurement and compliance testing. The implementation of PQ standards supports the integration of variable renewable energy sources while mitigating potential grid instability risks. These assessment methodologies provide valuable insights for ASEAN as the region scales up its renewable energy deployment. Establishing standardised PQ assessment frameworks, harmonised regulatory approaches, and advanced monitoring systems will be essential for ensuring seamless IBR integration into APG [19].

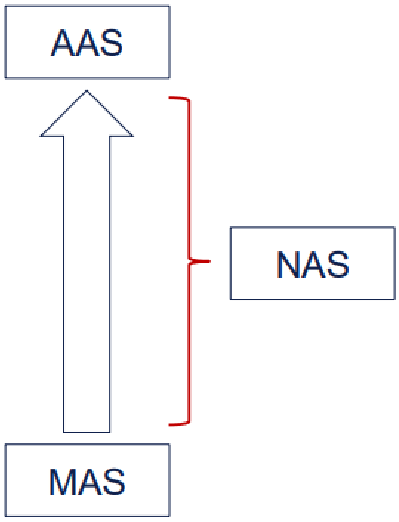


Figure 9 Integrated PQ Management Framework [4]

In the power quality management framework, AAS (Auxiliary Agreement System) refers to additional obligations imposed by NSPs to improve standards. The MAS (Management and Automation System) automates power activities to improve efficiency, whilst the NAS (Network Attached Storage) archives data for power quality analysis. These components facilitate effective electrical system management. Key voltage parameters related to high penetration of IBRs include:

6.2.1 Voltage Harmonic Distortion

6.2.1.1 Standards and Compliance

DNV Australia takes an integrated approach to managing voltage harmonic distortion, emphasising careful review and mitigation measures. Harmonic performance is tested using IEC TR 61000-3-6-2012 standards, with Network Service Providers (NSPs) establishing emission limitations for each project. The analysis only defines integer harmonics, with an alpha exponent factor of 1.0 across all harmonic orders, as specified in IEEE Standard 519-2014. DNV uses advanced Python automation tools in conjunction with DigSILENT PowerFactory to undertake extensive voltage harmonic distortion experiments, which require around 8000 simulations. These technologies allow DNV Australia to efficiently identify and handle harmonic non-compliances, ensuring effective management of the harmonic consequences associated with the widespread use of IBRs.

6.2.1.2 Case Study

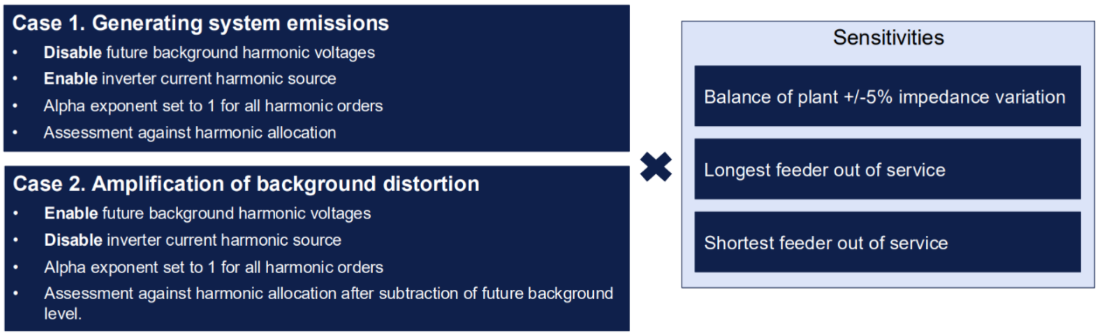


Figure 10 Harmonics Distortion Case Study [4]

To maintain grid stability and compliance, DNV Australia's approach to regulating voltage harmonic distortion includes extensive case studies concentrating on two major scenarios as well as sensitivity analysis. In Case Study 1, DNV Australia blocks future background harmonic voltages while enabling inverter current harmonic sources with a uniform alpha exponent of one for all harmonic orders. This configuration enables DNV Australia to evaluate harmonic allocations under a variety of operating situations, such as balanced plant impedance fluctuations and feeder failures. Case Study 2 takes on the amplification of background distortion by enabling future harmonic voltages while suppressing inverter present harmonic sources, all with an alpha exponent of one.

6.2.2 Voltage Fluctuations (Flicker)

Table 6 Flicker Emission Allocation Limits (AAS) for Short-Term and Long-Term Indices

Variation	Flicker Emission Allocation Limits (AAS)
Short-Term	0,35
Long-Term	0,25

DNV Australia manages voltage Emission Allocation Limits (AAS) fluctuations (flicker) by assessing flicker severity using short- and long-term indices (Pst and Plt), governed by emission limits set by NSPs based on IEC TR 61000.3.7. Operational data from Original Equipment Manufacturers (OEMs) on different network angles and operational scenarios (continuous, switching) is used. Calculation methods based on AS 61400.21-2006 standards consider a variety of operational scenarios, including continuous operation, switch-on events at 10% and 100% of rated power, and switch-off events at 100% of the rated power. The approach prioritises the lowest fault level scenario to achieve compliance with rigorous flicker Emission Allocation Limits (AAS) of 0.35 for short-term and 0.25 for long-term flicker severity.

6.2.3 Voltage Unbalance

DNV Australia manages voltage imbalance by ensuring regulatory standards listed in the National Electricity Rules (NER). This involves balancing the voltage generated in each phase and the current consumed when no power is provided, as specified in the

NER. To ensure compliance with these criteria, the examination uses data given by equipment makers. DNV Australia certifies that inverters and producing systems properly manage negative sequence currents to maintain symmetrical grid voltages and reduce unbalanced circumstances at connection points, hence promoting grid stability and operational dependability.

6.3 Great Britain

Great Britain's (GB) electricity grid is undergoing a significant transformation, shifting from traditional synchronous generators to IBRs as part of its renewable energy transition. Unlikely synchronous generators, which inherently provide inertia to stabilise the grid during disturbances by resisting frequency fluctuations, IBRs commonly used in solar and wind energy systems who lack this inertial response. As a result, the decreasing inertia levels present new challenges for grid stability, requiring advanced solutions to ensure a secure and resilient power system while meeting energy sustainable targets.

One of the key approaches to addressing these challenges is through the Wide-WAMS, which enhances real-time grid stability management by providing high-speed, synchronised measurements. By leveraging real-time control strategies and system-wide monitoring, grid operators can improve their ability to detect and respond to frequency deviations and instability risks associated with high-penetration renewable energy sources. These lessons from Great Britain's experience highlight the growing need for innovative stability solutions as power systems worldwide transition towards cleaner energy sources [20].

On 9 August 2019, GB's electricity grid suffered a network weakening and instability costing the system a cumulative power loss of more than 1,130 MW of generation within around 1 second of the fault, affecting 1.15 million customers [21]. The fault event started with a lightning strike which caused a fault on one of the 400 kV lines, causing a vector shift tripping at the local distribution networks. The voltage control system at the Hornsea 1 wind farm which was expected to respond to the impact of the transmission system fault, did not react as expected and became unstable, reducing 737 MW of its power generation. Shortly after, the steam unit at Little Barford (244 MW) station in Bedfordshire disconnected from the transmission system due to the speed deviation. A faster response time for protection equipment, a faster and more accurate measurement system, and responsive coordination between the measurement unit and protection equipment are needed to reduce the damage done by such conditions.

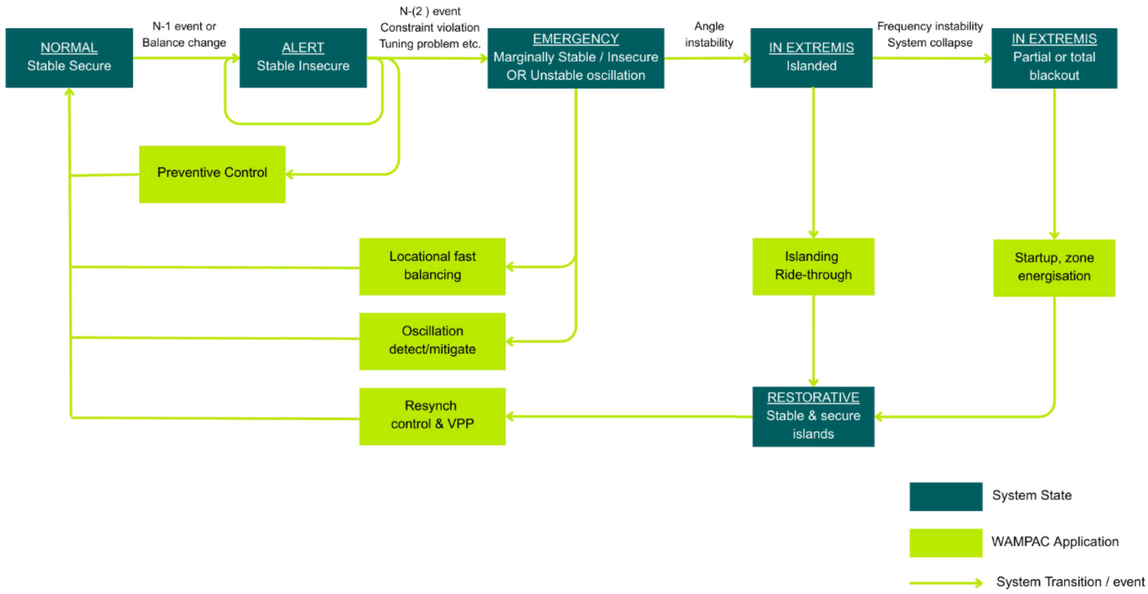


Figure 11 Typical WAMPAC Operation Diagram in Various System States [20]

The complexity of modern electrical power systems is steadily increasing with the penetration of massive amounts of asynchronous renewable generation. This generation that is connected through inverters reduces the inertia of the Grid and significantly changes how today's power system operates. These characteristics require shortened power system response time and strategies for dealing with the grid's reduced Inertia and weakened system strengths. WAMPAC recovery mechanism started to be applied when an N-1 contingency event or power imbalance (between supply and demand) occurred with preventive control such as a defence scheme mechanism applied to the system. Locational fast balancing and oscillation detection and mitigation measures are applied in the event of N-2 contingency, constraint violation, and tuning problems. The following table lists the function of each WAMPAC application and where those features have been applied.

Table 7 The Function of Each WAMPAC Application

Function	Description	ICE	AUS	UK
Locational Fast Balancing	Fast response to disturbances; reducing angle, frequency deviation, and ROCOF; avoiding spurious loss-of-mains trips and larger system splits	X	X	X
Islanding Ride-through	Balancing a zone as it transitions to island operations due to power balance or network disturbances	X	X	
Startup & Energisation Island Growth	Black-start restoration service co-ordinating balancing multiple DERs and network switching for stable island operation			X
Resynch Control & VPP	Controlling the process of bringing island zones together and restoring normal operations			X
Oscillation Detect/ Mitigate	Fast identification of a growing oscillation, determine source vs. sink, and trigger a control change or breaker opening.	Future - all		
Preventive Control	Identify stress. Dispatch to restore stable/secure operation before a critical condition.	X	X	X

Looking at the case of Great Britain, a wide area monitoring system applied with synchrophasor technology is integral in maintaining system stability. PMUs instantly detected the local ROCOF at the time of disturbance, supplying information on the potential loss of mains event in the power system; hence, providing necessary data for defence actions to be taken in preventing cascading system tripping and blackout.

What is Synchrophasor and Why is it Important in IBRs?

As the energy sector shifts towards renewable energy integration, power grids are increasingly dominated by IBRs such as solar PV, wind power, and BESS. This transition introduces new grid stability challenges, particularly in frequency regulation, voltage control, and power quality management.

The current state of the power system uses a system called SCADA, which is used for controlling, monitoring, and analysing industrial devices and processes. The main components of a SCADA system include a field device in the form of remote terminal units (RTUs), or PLC connected to the central control unit via specific communication protocols such as Modbus, DNP3, or OPC [22]. Given its technological maturity, SCADA has been widely implemented for power system control and monitoring, enabling power system operators to extract real-time wide-area measurement data and take actions remotely upon any occurring disturbances [23]. Despite its technological advancements, the SCADA system has certain limitations in managing inverter-dominated grids, as outlined below:

7.1 SCADA System Only Provides Steady-state Data

In a time of rising distributed energy resources, it is possible for electric power to flow bi-directionally, either from the grid (supplied by utility-scale generators) to consumers or from distributed generators to the grid. Thus, load angle/ phasor measurements in a dynamic manner (continuous) should become mandatory to monitor the flow of power and to ensure the stability of the grid frequency. SCADA system however provides steady-state or discrete data to determine whether the system is operating within the normal parameters or not. Such measurement is done due to the limitation of the measurement equipment in RTUs to send data continuously, so the SCADA system samples the acquired data and linearises the inputs to become presentable measurement data in the Human Machine Interface (HMI). This approach tends to be insufficient for detecting and predicting transient or dynamic events that occur during disturbances or faults, which may lead to equipment failures or cascading tripping, to some extent. Therefore, advanced SCADA systems often integrate additional functionalities such as machine learning algorithms and predictive analytics to analyse historical data and real-time sensor readings to identify patterns and anomalies that might indicate impending faults or process deviations [24].

7.2 SCADA System has a Low Sampling and Measurement Rate

In power systems data acquisition, the measurement unit typically samples the electricity using sample-and-hold (S&H) circuits, analog-to-digital converters (ADCs), digital signal processors (DSP) or field-programmable gate arrays (FPGAs), and processing and interfacing units. The sum of the latencies caused by the multiple data processing stages defines the performance of the measurement units in regard to the maximum sampling frequency, known as the sampling rate. Higher sampling frequency will output more accurate data, since the data acquisition process acquired plenty of samples, creating a precise interpolation [25].

While the SCADA system has been reliable in measuring power system data, it has some limitations in the sampling rate. A publication from 2020 studied the difference between micro-phasor measurement units and SCADA in the distribution network. The research stated that SCADA acquires 1 sample of data every 2-4 seconds, while PMU or micro-PMU could sample 10-120 data per second, which is more than 400 times more data sampled per second. As previously mentioned, higher sampling frequency means higher data accuracy. The research reflects this theory as the micro-PMU presents around ± 0.05% errors [26].

7.3 Most SCADA Systems do not Provide Load Angle/ Phasor Measurement

A phasor is defined as a vector representation of the magnitude and phase angle of an AC voltage waveform, typically represented by a unique complex number of the sinusoidal waveform formula. Phasor angle could be used in determining the power flow direction, making it useful for fault location finding in the distribution network and detecting reverse power flow, a commonly occurring issue in recent years due to the rise of distributed energy resources.

Most SCADA systems measure power systems data in static form, which will later be compiled and interpolated to be presented in a dynamic form. PMUs (or micro-PMUs), observe time-synchronised, dynamic state data by measuring the load angle/ phasor angle. The phasor microprocessor in the micro-PMU executes the phasor calculations based on the analog inputs, and the calculated phasors are combined to form positive sequence measurements.

Synchrophasor is a measurement of the phasor of the fundamental frequency component in a periodic waveform of an electric quantity (e.g., voltage, current) using a common time reference, typically the Universal Time Coordinated (UTC). "Synchro" refers to the measurement's temporal component. A signal is a function that communicates data about a phenomenon. "Phasor" refers to the representation of a sinusoidal signal wave shape, including magnitude, phase angle, and RMS magnitude of the current or voltage sine wave. Synchronised measurements of current and voltage phasors are taken from PMUs, which can also be used to derive parameters such as frequency and phase angle. PMU is a device which measures voltage and current synchrophasors, frequency, and ROCOF, while SCADAs measure RMS voltages, currents, and real/ reactive power analogically [27]. To ensure effective integration into power systems, synchrophasor technology exhibits several key characteristics that enhance real-time monitoring, data accuracy, and grid stability:

- Small data set
- Common reference – common GPS reference to utilise estimated phasor angle for monitoring actual phase angle difference
- Low communication bandwidth (Kbps to a few Mbps)
- Lower device processing speed: provide near-real-time data at the control centre
- Reduced storage – High but manageable
- Cost reduction and can be used for various application

Building on these key characteristics, synchrophasor technology offers significant benefits in transmission system operations, particularly in enhancing grid stability, preventing blackouts, and improving real-time monitoring, as outlined below:

- Synchrophasors are useful for detecting undamped electromechanical oscillations due to their high sampling rate
- Real-time PMU data can predict system instability and optimal grid disconnection, preventing blackouts through the analysis of angular oscillations
- PMU data can be used to analyse the generation loss based on the frequency deviations even in the post-disturbance period
- ROCOF PMU signalling speed provides insight into the order of a hundredth of Hz/s, important for characterising dynamic behaviours such as oscillations

Synchrophasors will become more essential in future power systems that rely mostly on IBRs. In contrast to standard SCADA systems, Synchrophasor technologies give high-speed, synchronised voltage and current phasor measurements at up to 120 samples per second. This feature allows for the exact monitoring of dynamic grid conditions affected by DERs, such as rooftop solar panels, energy storage, and electric cars. These resources produce fast swings and bidirectional power flows, calling into question the grid's standard design assumptions.

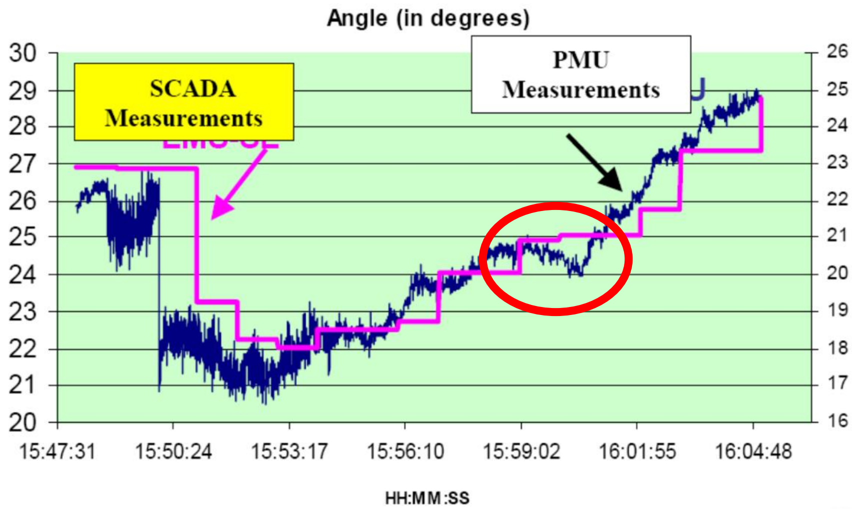


Figure 12 SCADA vs. PMU Measurements [23]

As shown in **Figure 12**, the PMU measurement data shows real-time fluctuations of the voltage due to its higher sampling rate, while SCADA shows linearised data with its lower sampling rate. The SCADA unit uses interpolation to *"connect the dots"* of the acquired data, creating a discrete measurement graph. Referring to the graph, SCADA measurements also lag behind the PMU measurements, due to the input latency that the SCADA system endures. The red circle in **Figure 12** highlights the significance of the sampling rate in the measurement of power system data. While the SCADA measurement shows a linear step, the PMU measurement detected a sag in the phasor angle thanks to the high sampling frequency of the PMUs.

The relevance of synchrophasors stems from their capacity to improve grid stability, reliability, and efficiency. They enable sophisticated applications such as Distribution Linear State Estimation (DLSE) and Fault Location, Isolation, and Service Restoration (FLISR), which are critical for responding quickly to faults and disturbances in distribution networks [27]. Synchrophasors allow utilities to improve grid operations, detect abnormalities quickly, and prevent possible grid instability concerns before they worsen. This feature is especially important for guaranteeing the resilience of contemporary power systems to unforeseen occurrences and increasing overall system performance.

***Table 8** Differences between SCADA and PMU Measurement*

Characteristic of Sensors	Transmission		Distribution		
	SCADA	PMU/ Synchro-phasor	Smart Meter	SCADA	μPMU/ Synchro-phasor
Spatial Resolution	Very dense	Becoming dense	Dense	Sparse	Extremely sparse
Temporal Resolution	1-5 s	< 33 milliseconds	1 min - 1hour	1-5 seconds	< 16 milliseconds
Latency	2-4 s	< 1 millisecond	Few hours to days	2-4 seconds	< 50 milliseconds
Time-synchronised	No	Yes	No	No	Yes
Angle	No	Yes	No	No	Yes
Monitoring & Control	Local to some extent	Wide area	-	-	Wide area
Resolution	1 sample every 2-4 sec	10-120 samples per sec	-	-	512 samples per cycle (25khz)

Synchrophasors can measure angles with accuracies of ±0.01 degrees, making them more precise than SCADA [26]. This degree of information is required for studying grid dynamics influenced by intermittent renewable power and sensitive loads. Furthermore, synchrophasors promote the efficient integration of renewables by allowing grid operators to regulate voltage variations and lessen the effects of DER-caused grid disruptions. Their capacity to record high-frequency components such as harmonics and subharmonics improves grid monitoring capabilities, providing steady and dependable energy delivery despite rising system complexity.

In conclusion, synchrophasor are a breakthrough technology that tackles the issues created by the fast increase of IBRs in modern power systems. Their implementation provides significant advantages over traditional SCADA systems, such as increased situational awareness, greater grid resilience, and optimum operating efficiency, making them critical for future grid infrastructure.

What's Next in Strengthen the ASEAN's Grid Power System?

The rise of inverter-based power generation will become a norm in the coming years. According to the AEO8, the ASEAN region is looking to add more renewables in the future, setting the increase in renewable energy share to 69.4% in installed capacity [28]. With the increasing integration of IBRs, the imminent challenges associated with variable renewable energy should be taken seriously amongst power system operators in the ASEAN region. The challenges may include but are not limited to, harmonic distortion, frequency stability issues, and voltage anomalies. Through the region-wide application of smart grid technologies, such as synchrophasors, WAMPAC, and advanced metering infrastructure, those challenges could be tackled to allow safe, secure, and reliable electricity distribution to consumers.

A structured and phased approach to synchrophasor technology implementation can serve as an effective model for ASEAN, starting with pilot projects in strategically selected regions. These pilot projects would allow grid operators to evaluate the effectiveness of PMUs and WAMPAC in oscillation detection, grid stress analysis, and system stability enhancement before full-scale deployment. By leveraging real-time synchrophasor data, ASEAN's GSOs can enhance situational awareness, optimise frequency response, and improve operational decision-making in managing high-penetration IBRs that could be adopted to assess the impact of DER integration and cross-border power trade [23].

Despite the technical benefits, each approach requires distinct planning processes, with different trade-offs in grid coordination, investment requirements, and system efficiency along with the high capital costs associated with upgrading existing infrastructure, deploying advanced metering systems, and integrating communication networks remain a significant barrier to widespread adoption. The complexity of large-scale smart grid implementation, which can follow either a top-down (supply-side) approach, focusing on generation control system enhancements, or a bottom-up (demand-side) approach, advanced metering and consumer-side energy management.

To ensure grid stability in an IBR-dominated future, further technical studies and knowledge sharing amongst ASEAN's GSOs will be essential to strengthen understanding of system inertia, dynamic grid behaviour, and emerging stability solutions. The deployment of synchrophasor technology and PMUs in transmission and distribution networks, alongside the integration of DERs to facilitate prosumer market participation, should be prioritised within the region. These advancements will not only support ASEAN's decarbonisation agenda but also enhance grid reliability and operational efficiency as the power sector transitions towards a more decentralised and sustainable future.

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ASEAN Centre for Energy
6th Floor, Jl. H.R. Rasuna Said, Block X-02
Kav 07-08, Kuningan, Jakarta 12950

aseanenergy.org
Phone: 62-21-527-9332
Fax: 62-21-527-9350