NSW DECARB HUB
Electrification and Energy Systems Network

UNSW SYDNEY

UNIVERSITY OF WOLLONGONG AUSTRALIA

White Paper

Securing Power Systems in the Renewable Revolution

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01

> **“ As these aging generators withdraw and retire, replacement services must be delivered on time to support higher levels of renewable energy...**
>
> Daniel Westerman, Chief Executive Officer, AEMO

Executive Summary

Australia’s power system faces two parallel imperatives: to rapidly decarbonise electricity as demand rises, and to urgently replace an ageing, largely coal-fired (synchronous) generation fleet.

To achieve both goals at least-cost, the replacement capacity will mainly consist of renewable resources, supported by energy storage and a small amount of gas-powered generation. These renewable resources will be mostly inverter-based (asynchronous), and increasingly decentralised. This offers an opportunity for Australia to reimagine how to deliver clean, affordable power in a way that is also reliable and secure.

The transition away from synchronous generation will change how we maintain power system security - especially inertia, fault current and system strength.[1] As AEMO highlighted in its 2025 *Transition Plan for System Security,*[2] the consequences of late or insufficient action are materially more severe than the costs of acting early. Delays in delivering replacement power system security services ultimately impose higher costs on consumers and increase the electricity network’s exposure to cascading system risks.

This white paper offers evidence-based insights to identify, and pose pathways to address, the open questions that must be resolved to secure Australia’s electrical networks. It does so by synthesising and categorising the current literature and views collected through engagement with industry, government and academia.

Many of the recommendations are drawn from a workshop hosted by the NSW Electrification & Energy Systems Network and UNSW Energy Institute on Securing Power Systems in the Renewable Revolution, which was held on 9 September 2025 with more than 40 senior energy sector stakeholders. The white paper seeks to act as a reference for investigations that address the open questions, including early and well-targeted investment in testing, validation and system-level capability development.

The key to successfully addressing these questions is doing so in a coordinated, integrated way that is facilitated by partnerships between industry, academia and government agencies.

Thus, the white paper makes the following recommendations:

- Establish a national approach to electrification to facilitate investment in activities that will accelerate the adoption and integration of new technologies. This includes advanced inverter controls to deliver power system security measures that are robust and fit for purpose, supporting least-cost outcomes for energy consumers.
- Undertake an immediate and detailed investigation into the behaviour of inverter-based resources and protection relay performance during grid disturbances. This will resolve uncertainty related to how protection systems respond at high levels of wind and solar generation alongside battery energy storage systems.
- Deliver a wide area network digital twin of critical parts of the National Electricity Market, simulating future scenarios to identify and resolve integration and control issues that could affect power system security. This will help avoid loss of supply (blackouts) and de-risk the evolution of the grid.
- Establish a representative working group of deep expertise to inform policy, regulation and standards that can respond to rapid technology developments.

The key finding of the white paper is that a national approach to electrification will be crucial to resolving the unresolved questions related to power system security.

The 20 open questions outlined in Section 8 (Recommended Actions) highlight complementary activities that should be addressed together. The questions focus on events that power systems must effectively respond to, and recover from within fractions of a second.

Contents

Securing Power Systems in the Renewable Revolution.

Preface

Discussion Themes

Recommended Actions

Appendices

02

Introduction

> **Coal fired electricity has generated the heartbeat needed to keep the grid stable. As coal retires, we are introducing new large-scale batteries and motors to maintain this heartbeat in a clean energy system that is resilient and can better adapt to the fast changes that will happen with a renewable energy grid.**
>
> Marie Jordan, Former EGM Networks, Transgrid

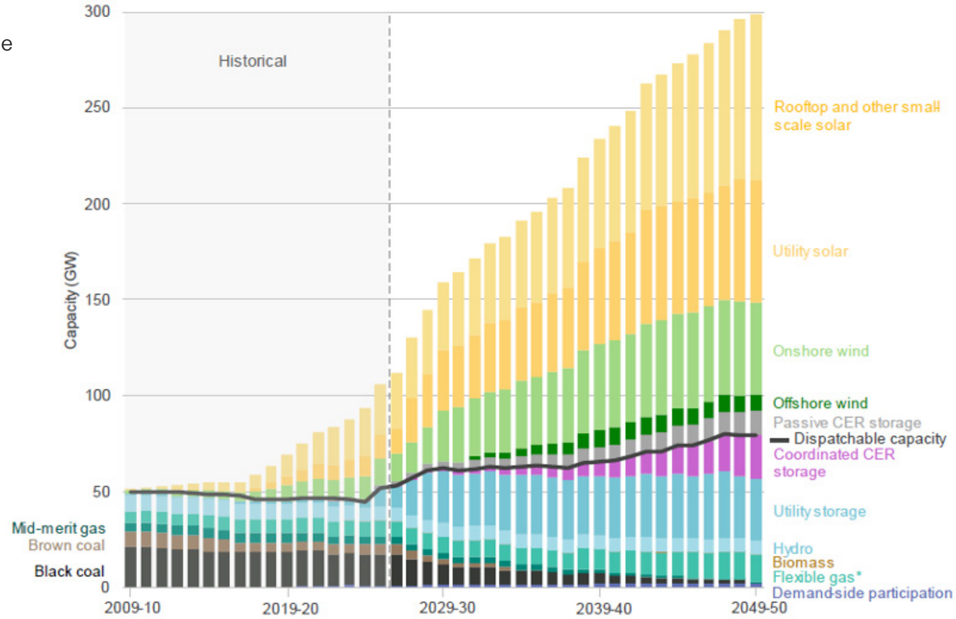
Australia is moving rapidly to an electricity system powered mostly by inverter-based resources, concurrent with our digital transformation of the power system.

As stated by the Australian Energy Market Operator (AEMO), "The future power system must be capable of operating at up to 100 per cent instantaneous renewable energy in the coming decade". This is not only being driven by the imperative to decarbonise, but also to replace our ageing, largely coal-fired, generation fleet. The ensuing decline in legacy synchronous machines will have a significant impact on the way we ensure power system security, specifically inertia, fault current and system strength.

While this may be perceived as a challenge to many energy sector stakeholders who are seeking to balance multiple objectives - most importantly, to "keep the lights on" – it can also be approached as a unique opportunity. The shift towards renewable energy sources connected by inverters provides an opportunity to move towards a more agile system, mostly powered by low- to no-marginal cost wind and solar PV generation, firmed by hydro, batteries and gas generation (Figure 1). This may also offer the benefit of the inherent reliance that is borne of distributed network architecture. Realising these benefits, however, requires informed and timely choices in the allocation of financial and human capital.

As AEMO has highlighted in the 2025 Transition Plan for System Security, the risks are asymmetric: the consequences of late or insufficient action are materially more severe than the costs of acting early. Delays in delivering replacement security services increase reliance on operational interventions, system directions and emergency mechanisms, ultimately imposing higher costs on consumers and increasing exposure to cascading system risks. In this context, early and well-targeted investment in testing, validation and system-level capability development is warranted, even where some technical questions remain unresolved.

Figure 1. Projected generation capacity mix (GW) in the Australian Energy Market Operator's Step Change scenario in the 2026 Draft Integrated System Plan (AEMO, 2025)



Notes: Projections for "Rooftop and other small-scale solar" and "CER storage" are forecast as outlined in the 2025 IASR. "Rooftop and other small solar" includes forecast residential and commercial rooftop photovoltaic (PV) systems as well as larger distributed PV systems referred to as PV non-scheduled generation (PVNSG) systems. "Utility solar" also includes other distributed PV systems, optimised through the ISP assessment process. "CER storage" means consumer energy resources such as batteries and EVs. "Flexible gas" includes gas-powered generation and potential hydrogen capacity.

The importance of this topic is well-documented, as represented by the following quotes from key energy sector stakeholders in Australia:

> "For decades, system security services have been a by-product of coal-fired power generation. As these aging generators withdraw and retire, replacement services must be delivered on time to support higher levels of renewable energy produced by residential rooftops and commercial scale generators."[3]
>
> "What we are even more heavily focused on now is that system security element. We're getting to a point now where each move on the chessboard matters. Each change to the power system now is more delicate than it has been previously."[4]

Daniel Westerman, Chief Executive Officer, AEMO

> "The NEM's transition to a system dominated by VRE is underway and will continue to accelerate, as AEMO's (Australian Energy Market Operator) 2024 Integrated System Plan (ISP) shows. It is critical that the system can operate within its technical operating envelope as synchronous generators continue to retire. The (AEMC Reliability) Panel recognises the work AEMO is undertaking to identify the key milestones required to securely transition the power system.
>
> However, the Panel is of the view that to keep pace with the energy transition, security needs must be identified earlier so that timely investment can occur. Security risks are emerging faster than expected. For example, system strength and minimum system load have become critical risks earlier than expected, and market interventions have been needed to maintain system security."

Tim Jordan, AEMC Commissioner / Former Chair of the Reliability Panel 23 April 2025[5]

> "The future power system must be capable of operating at up to 100 per cent instantaneous renewable energy in the coming decade. To support the amount of wind, solar and hydro required we must invest in a diverse range of options to keep the system strong,"

Marie Jordan, former EGM Networks, Transgrid

There are diverse views among Australian energy sector stakeholders on how to deliver power system security under high penetrations of inverter-based resources (IBR). A summary of these views is outlined in Appendix A - Stakeholder views on approaches to power system security.

Evidence-based investigations are needed to best determine economically- and technically-efficient alternatives to achieving power system security across the wide range of credible operational scenarios. This paper has the following aims to address this need:

- To synthesise the range of views captured on achieving power system security under a high penetration of IBR.
- To identify the critical open questions and gaps in evidence required to accelerate the adoption and integration of new technologies, pertaining to topics such as grid-forming inverters, to deliver power system security in a way that is technically optimal and supports least-cost outcomes for energy consumers.
- To act as a reference in shaping investigations that will contribute to resolving these questions.

The following sections explore the core topics that must be addressed, drawn from discussions held at a workshop at the University of NSW on "Securing Power Systems in the Renewable Revolution" on 9 September 2025, hosted by the Electrification & Energy Systems Network and UNSW Energy Institute.

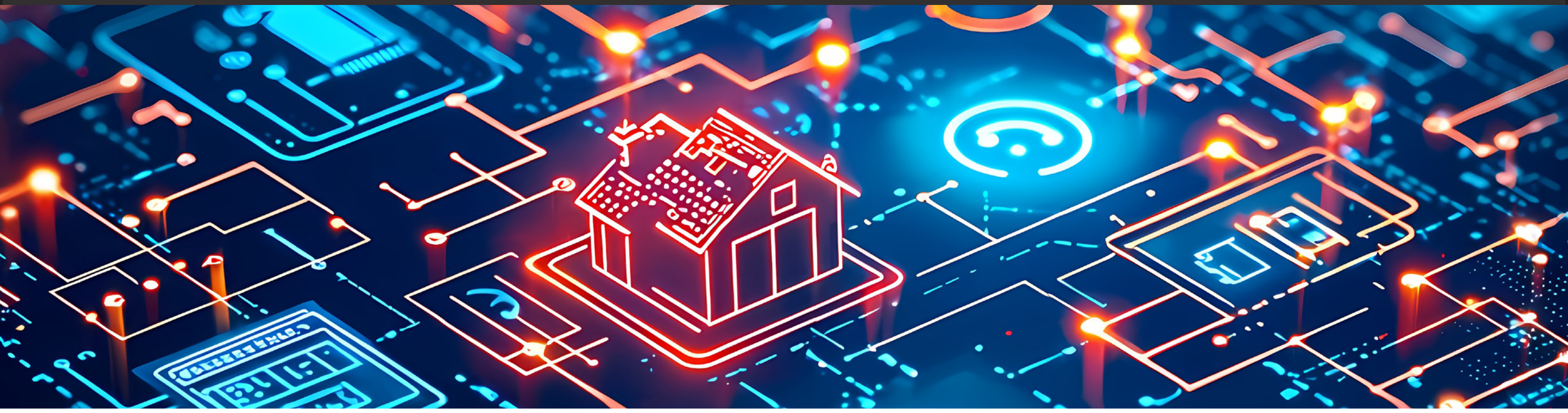
The paper is structured to explore:

- principles and future scenarios.
- power system security and protection.
- testing, validation and risk mitigation; and
- regulatory, market & institutional issues.

The paper concludes with Recommended Actions on the investigation questions and pathways to address the critical knowledge and evidence gaps.

03

Principles & Future Scenarios



This section primarily focuses on the immediate response of the system to grid disturbances that are typically initiated by an event window from a sub-cycle timescale to typical clearing times of 4-10 cycles (<0.2sec).

These are the events that rely on inertia and system strength. As Australia's growth rate in renewables, and the retirement of coal fired thermal plants continues, there is an urgent need to understand the support mechanisms that inverters can provide to the system in these sub-second timescales. Such terms as 'grid forming', 'grid-following' and 'virtual synchronous generator' modes have highlighted some of the advances that newly developed control code for inverters can provide. However, new technologies need to be tested online in a controlled environment to provide confidence that the critical aggregate responses are both understood and delivered.

Furthermore, the complexities of navigating a transition that requires both 'conventional' and 'advanced' network assets to function in concert with one another, and then for the conventional assets to be phased out necessitates not just the impact that the new technologies can have in the present, but also how they will contribute at scale once the services provided by conventional technologies can no longer be relied upon.

Inverters are a key enabling technology for the energy transition. Inverter systems are fast acting and can respond quickly to changes to the conditions of the electrical grid. The changes to the grid, or grid disturbances, can occur regularly due to operational changes such as transmission line switching, large load or generation changes (e.g. weather), or through the correct operation of protection systems, generator trips and other contingencies. However, with advanced inverters the potential for instability is much higher due to the fast response in the controlled inverter. For some years, grid-forming (GFM) inverter proponents have stated the technology can contribute all the system support mechanisms in a future grid dominated by inverter-based resources. The veracity of which still needs to be fully tested at a network level.

To enable this inverter-facilitated future, the following investigation questions have been prioritised by industry, government and researchers:

- What is the need for synchronous machines now, during the transition and beyond?
- What mix of synchronous condensers, grid-forming and grid-following inverters is necessary? What are the boundary conditions?
- If required, can inverter-based resources (IBRs) provide all power system security services to the system?
- How would a "Pilot" Future State of the Network be designed to provide confidence of "feasibility at scale" to regulatory authorities?
- If inertia is not necessary for power system security, what IBR penetration thresholds will demand innovative system design and operational approaches?

The challenges related to power electronics-enabled systems include limited bandwidth (with low switching frequencies), limited overcurrent potential and rapid response times. If the equipment becomes part of wide-area control system, then communication latency becomes challenging for feedback control systems at these short timescales of note.

Considering IBR diffusion throughout network

With increasing penetrations of inverter-based resources, the challenge of maintaining stability of the grid that has a mix of conventional steam- or gas-driven synchronous generation in parallel with inverter-based resources becomes more complex. Large portfolios of battery energy storage systems are likely in both the transmission and distribution networks. The tensions between distribution assets and transmission-based assets are also only just revealing themselves. There is a strong possibility that a system with a mix of both will offer a pragmatic solution.

These poorly understood areas resolve into another investigation question:

- What is the appropriate mix of distribution and transmission-based assets to best operationalise security services?
- How does this mix change with location, asset availability, demand, supply and penetration of generation, load features and network arrangement?

There are limitations to inverter-based resources that are fundamentally different to the limitations of conventional generation techniques. For inverters, these limitations are imposed by both physical laws and software implementations. These factors lead to uncertainty and complexity in the responses of a diverse portfolio of inverters. Furthermore, technological advances in power semiconductors have led to a spread of switching frequencies in inverter-based equipment ranging from 1-2 kHz to 150 kHz depending on chosen solution providers. This variation will become wider as power semiconductor performance continues to improve. There is a direct link between switching frequency and inverter performance.

Contemplating 100% IBR Operation

One potential future state involves a 100% power electronic enabled electrical grid. Under this scenario, such systems will be highly dynamic, and the response to grid disturbances will vary depending on multiple factors including the time of year, day, and the grid demand and its variance. Variances in the availability and geographical locations of system security provisions will need to be better understood in order to operationalise power system security services.

Critical to any power system is the need to remain stable over the first few milliseconds of a major disturbance or contingency event. The tools to do this with a conventional grid are tried and tested with over 100 years of experience informing a mature and well-understood set of principles. We must rapidly gain the same level of understanding and operating principles about inverter responses and their impact on power system security. We have limited time and with little tolerance by energy consumers of sub-optimal controls and decisions.

Embracing a National Approach

The imperative is to understand the practical challenges of delivering a decarbonised energy system with appropriate power system security measures through inverter-based resources and synchronous generation that is safe, secure cost-effective considering stability, protection and safety. The paper's authors recommend these investigation pathways are addressed within the context of a national approach to electrification: to de-risk and accelerate the adoption and integration of new network technologies.

Principles & Future Scenarios: investigation pathways

1. What is the need for synchronous machines now, during the transition and beyond?

2. What mix of synchronous condensers (SynCons) and inverters - both grid-forming (GFM) and grid-following (GFL) is necessary? What are the boundary conditions?

3. If required, can inverter-based resources (IBRs) replace 100% of inertia services provided to the system?

4. How would a "Pilot" Future State of the Network be designed to provide confidence of "feasibility at scale" to regulatory authorities?

5. If inertia is not necessary for power system security, what IBR penetration thresholds will demand innovative system design and operational approaches?

6. What is the appropriate mix of distribution and transmission-based assets to best operationalise security services?

7. How does this mix change with location, asset availability, demand, supply and penetration of generation, load features/criticality and network topology?

04 Power Systems Security & Protection

For more than a century, power system protection has relied on fault current. In traditional synchronous machine-dominated grids, faults generated several multiples of rated current, providing a clear, rapid, and reliable signal for protection relays. This worked because synchronous machines inherently produce high short-circuit currents, making abnormal events easy to discriminate from normal operation.

IBR Current Limits Challenge Fault Discrimination

As grids shift toward inverter-based resources (IBRs), the efficacy of this mechanism weakens. Like synchronous generators, inverters are required to ride through faults to avoid a cascading loss of generation. But to protect their own solid state switching devices, inverters are current-limited—typically around 1.1–1.2 per unit of rated output. As a result, fault current loses its discriminating power; a fault may appear little different from a heavy load, undermining traditional overcurrent-based protection schemes commonly used in distribution networks.

On the other hand, transmission networks in Australia typically employ modern numerical relays for protection, with differential protection as the primary scheme and distance protection as a backup when communication networks are unavailable. These protection elements rely on current and voltage measurements. Whilst the aggregate fault current contribution from grid-forming inverters may be adequate for these protection schemes to distinguish faults from normal operating conditions, there are reliability uncertainties across the diversity of operating conditions. AEMO recognise that the term “protection-quality fault current” is not currently defined in Australian Standards or the NER.[6] Fault current has magnitude, duration and waveform properties that all need to be understood in the transition to IBR resources. The lack of definition makes IBR OEM claims around the adequacy of their technology for dependable network protection hard to verify and contributes to reliability uncertainties.

To address this uncertainty, some network operators are installing synchronous condensers (SynCons), which can provide additional short-circuit current, system strength, inertia, and reactive support. While SynCons restore some fault current capability for conventional protection, they are costly, fixed function assets.

SynCons: no Panacea

There are potential risks of reliance on SynCons for power system stability. For example, lead times can be many years, during which coal generation outages are more likely, outages may reduce stability margins. SynCons can themselves trip, resulting in sudden step-changes to available inertia and fault current whilst IBR resources are modular and distributed reducing the risk of a step change in availability. In addition, questions remain about how oscillations can be damped under low-load conditions with fixed and hence relatively high levels of inertia.

For these reasons, there are several no-regret actions in advancing understanding of how GFM inverters behave and interact with protection systems during fault conditions. If reliability uncertainties can be addressed, costs to consumers would fall and confidence would increase in power system security with high IBR penetrations.

A Proposed Approach

With effective specifications IBR-based battery systems can potentially be designed to provide overload / fault current of known magnitude, duration and waveform characteristics. Thus, system fault current can be increased even if each specific system is limited. Network protection systems are sized to the aggregate response of all generation in the relevant node, not any one generator.

There are also potential additional parameters to fault current for managing systems security including dampening and synchronising torque. These metrics describe and can help control the system stability behaviour in an IBR-rich environment. Assets monitoring and controlling these properties can provide more discriminating, stability-oriented protection signals.

Looking ahead, system security planning could move from reliance on blunt fault current magnitude thresholds to hybrid, adaptive approaches combining additional Power System parameters.[8] Future network protection systems could recognise IBR fault current waveform characteristics beyond just magnitude. SynCons will continue to play a transitional role, but the long-term future lies in real-time stability monitoring and multi-parameter protection schemes, validated through digital twins, hardware-in-the-loop testing, and field demonstrations. The following investigation questions could explore these options.

These questions complement various AEMO reports[9 10 11]. The authors recommend the questions form the basis of a project to investigate IBR behaviour and protection relay performance during grid disturbances as part of a national approach to electrification.

Power System Security & Protection: investigation pathways

1. What is the definition of the term “protection quality fault current” into measurable and verifiable attributes?
2. What is the understanding of and how to evaluate IBR responses to credible grid disturbances and the compatibility with network protection settings?
3. How to evaluate the minimum fault current thresholds (magnitude, duration, waveform) required for dependable operation of representative transmission and distribution protection schemes?
4. To what extent can specifications and inverter system design increase or define the system fault current characteristics to ensure dependable power system protection?
5. Can future protection systems rely on different fault-current properties, not just the magnitude (e.g., waveform signature)[7]?
6. What control functions and specifications are required so fault current can be viably and reliably provided by inverter-based resources to deliver sufficient power system protection? To what degree? Are there alternative parameters?

05

Dynamic Behaviour & Stability

In the transition to greater proportions of fast-acting, inverter-based resources (IBRs) with renewables and energy storage, it is crucial to consider power system stability.

System stability control is transitioning from physics-defined, to control-defined. In a traditional system, synchronous generation has provided voltage, frequency and angular stability. In the transition state, power electronics through converter controls will couple with both the electromechanical dynamics of machines and the electromagnetic transients of the network.

It is important to consider how solutions that are electromechanically defined, such as SynCons, will respond in faster acting systems, such as those with GFM inverters, that have lower inertia.

As outlined by AEMO in the Grid Forming Access Standards Approach Paper,[12] the three key requirements for GFM inverters to provide stability are stable references, network support and robustness. Stable references refer to the ability of assets to exhibit voltage-source-like-behaviour (acting like a voltage source), immunity to disturbances (including voltage, frequency and phase angle jumps and their composition in any form), resistance to harmonic oscillations and independent operation that is essential for black start capability.

Network support refers to the provision of voltage support, fast frequency response and damping of oscillations, to support local and inter-area events. Robustness refers to the GFM inverter's ability to coordinate with other power system equipment and support the grid to withstand external variation, particularly under weak grid conditions and system restart.

In a system relying increasingly on GFM inverters to provide system stability services, analysis tools and the principles of control do not fundamentally change but they must consider additional factors.

These factors include:

- A more complex network with its spatial and temporal patterns
- More complex electronic components compared with traditional mechanical components
- IBRs with diverse ratings and control schemes
- A large variance in operating conditions
- Cybersecurity threat vectors, particularly with inverters themselves
- The unknown unknowns of maintaining stability in power electronics-defined power systems.

The first concept to be explored is: how the behaviour of power electronics (both in GFM and GFL modes of operation) and SynCon changes under different conditions - in both a controlled laboratory environment and in the field.

Consequences of Spatially Separating Services

The decoupling of generation, inertia and fault current through the deployment of IBRs and SynCons means that power injections and inertial responses may no longer originate from the same electrical location. This raises questions around possible delays in response.

More specifically, several investigation questions are proposed:

- What impact do GFM and GFL converters have on system stability (specifically small-signal stability) when co-located with SynCons? What additional impacts are experienced in remote locations? What are the critical parameters for tuning the operation of these co-located systems?
- How to optimise the allocation and proportioning of GFM converters, GFL converters and SynCons according to network conditions? What is the operating tolerance band between them?
- Can we dynamically allocate the role of GFL and GFM converters based on the needs of the broader network?
- How should GFM inverter-based controls be configured over the longer timeframe (beyond the initial sub-transient / transient period)?
- How should GFM inverter-based controls be configured after reaching the equipment power / current limit?
- What is the resulting impact on supervising and protection elements, such as protection relays, and wide area protection schemes?

Is Faster Better?

The second control-related concept to be explored is the fundamental trade-off involved in the selection of the speed of response. Faster control action improves responsiveness of the system but can lead to controller interactions and small signal oscillations. Slower responses enhance stability in a traditional system, dominated by synchronous generation, but are less effective in systems with lower inertia.

The power converter delivering active power to the main grid has a non-passive nature in the frequency range near the fundamental frequency, so exceptions need to be in place even before specific stability criteria are considered.

Thus, the following investigation question is proposed:

- How can faster dynamic response be enabled in a way that can guarantee behaviours across all conditions, including rapidly changing conditions that can conflict with performance objectives?
- How can GFM technology improve on existing responses from synchronous generators?
- How can GFM control be designed and GFM dynamics be limited or shaped to maintain responsive and robust performance across a wide range of system conditions?

Barriers to Accurate Modelling

A third concept to be considered is the challenge between small signal and wide area stability models. Accurate models are crucial for power system planning and system security, requiring continuous maintenance and updating.

However, open models are not readily available. This creates challenges relating to data sharing between OEMs, developers and operators, modelling vendor lock-in often leading to higher costs, and IBRs with "black box" features.

There is strong demand for alternative modelling approaches, particularly as the computational complexity increases with the proportion of inverter-based resources.

Solving these challenges could be achieved through the following investigation questions:

- How could new methods be enabled for:
    - impedance scanning and impedance bands for plants under different operating conditions,
    - data-driven stability analysis, and
    - control hardware-in-the-loop testing for wide-area and rapid testing
    - development of open-source models to facilitate the connection process
- Subject to commercial requirements, how could open-sourced or white-boxed models support the connection process?

In summary, it is crucial to consider both speed and interactions. GFM inverters are faster but faster is not always better. There are potential conflicts that must be investigated between local inverter control, responses by the power plant controller and further interactions with the wide area network.

Alongside the Power System Security & Protection recommendations these investigation questions would inform an IBR behaviour and protection relay performance project as part of a national approach to electrification.

Dynamic Behaviour & Stability: investigation pathways

1. What impact do GFM and GFL converters have on system stability (specifically small-signal stability) when co-located with SynCons? What additional impacts are experienced in remote locations? What are the critical parameters for tuning the operation of these co-located systems?
2. How to optimise the allocation and proportioning of GFM inverters, GFL inverters and SynCons according to network conditions? What is the operating tolerance band between them?
3. Can we dynamically allocate the role of GFL and GFM inverters based on the needs of the broader network?
4. How should GFM inverter-based controls be configured over the longer timeframe (beyond the initial sub-transient / transient period)?
5. How should GFM inverter-based controls be configured after reaching the equipment power / current limit?
6. What is the resulting impact on supervising and protection elements, such as protection relays, and wide area protection schemes?
7. How can faster dynamic response be enabled in a way that can guarantee behaviours across all conditions, including rapidly changing conditions that can conflict with performance objectives?
8. How can GFM technology improve on existing responses from synchronous generators? How can GFM control be designed and GFM dynamics be limited or shaped to maintain responsive and robust performance across a wide range of system conditions?
9. How could new methods be enabled for:
   - Impedance scanning and impedance bands for plants under different operating conditions,
   - Data-driven stability analysis, and
   - Control hardware-in-the-loop testing for wide-area and rapid testing
   - Development of open-source models to facilitate the connection process
10. Subject to commercial requirements, how could open-sourced or white-boxed models support the connection process?

06 Testing, Validation & Risk Mitigation

The transformation in project design, delivery, and operational practices across large-scale generation necessitates innovative approaches to modelling, control integration, compliance verification, and dynamic performance testing.

Effective implementation relies on continuous and transparent collaboration among developers, original equipment manufacturers (OEMs), network service providers (NSPs), network operators (NO) and AEMO.

As performance and compliance expectations evolve, traditional engineering practices and processes must be redefined through advanced analytical tools, enhanced competencies, and comprehensive validation frameworks to mitigate risks and support system security.

A comprehensive testing and validation framework should incorporate multiple layers of assessment to cover the performance, interoperability, and resilience of new technologies across all operating conditions. Different testing approaches offer unique insights before technologies are deployed into the field.

These approaches are used, to different extents, by OEMs, NSPs and AEMO but there is no complete or consistent methodology, especially at scale.

Such testing can progress through several complementary stages, including:

- **Simulation-based studies** enable early-stage validation of control algorithms, plant dynamics, and potential network interactions. These kinds of studies can be initially performed with generic models, to then include OEM's specific controllers (either as black-box or white-box).
- **Controller-hardware-in-the-loop (CHiL) testing** focuses on verifying controller, protection relays, and automation systems performance, where the device under test is influenced by the simulated grid (and vice versa). The setup of a CHiL testing platform may include, for example, a single inverter controller while the rest of the low-voltage equipment, such as meters, power plant controller (PPC), are modelled in the real-time simulation environment. In a more complex setup, all these models can be replaced by their hardware counterparts.
- **Power-hardware-in-the-loop (PHiL) testing** extends the CHiL testing capabilities by integrating real power hardware, such as converters, through power amplifiers into the simulation environment to evaluate actual energy exchange and system dynamics. Similar to the CHiL testing platform, in the PHiL setup, one or more devices can be included in the setup as model or as hardware. An additional feature of a PHiL testing setup is that, depending on power amplifiers' capacity, it can run with a scaled-down capacity (a few kW) or under full-rated capacity (for the device under test).
- **Wide-area network (WAN) studies** assess system-wide interactions between dispersed assets and control systems. They can be performed using pure simulation-based platforms or in a combined CHiL/PHiL environment with a single controller or device with a simulated electricity network.
- **Wide-area with combined power and control hardware-in-the-loop (PoCoHiL) testing** provides the most holistic validation environment. It allows for simultaneous device assessment, including interactions, control interoperability, communication delays, etc. with a large-scale representation of the electricity network.

Testing Sophistication Introduces Challenges

While these testing options provide valuable insights, they also introduce significant complexities. Interface requirements between simulation and hardware often depend on OEM-specific control architectures and communication protocols, requiring adaptable and modular setups.

Another critical challenge lies in ensuring the closed-loop stability of HiL testing. The combined configuration of the device under test and the simulators must interact in a stable, coherent way despite inherent interface delays, limited bandwidth, and amplifier dynamics.

Continuous maintenance of models is required to reflect evolving grid conditions and characteristics as well as network topologies. Upgrades of firmware are also needed to represent the latest control logic existing in the field. Moreover, technology progression introduces additional layers of uncertainty – the testing infrastructure must evolve in parallel with the grid, its assets, and the rapid advancements in deployed technologies to remain accurate and functional.

Multi-level Testing Comes With Benefits

Establishing such a multi-level testing capability provides substantial system and industry benefits. It allows for independent validation of emerging technologies, including grid-forming inverters, advanced distributed energy resource controls as well as the rapid testing and revision of control structures. It also enables flexible and accelerated connection assessments for new generation projects – informing future revisions of grid performance standards. Furthermore, the integration of PoCoHiL capabilities with WAN studies creates the underlying infrastructure necessary for the development of advanced testing facilities, supporting continuous learning and new technology testing.

Through systematic validation, and access to such testing infrastructure, analyses such as the optimal mix of grid forming, grid following, and complementary technologies like synchronous condensers can be identified and deployed to enhance system strength and security. The use of this testing infrastructure will also promote the development of a skilled technical workforce, equipping engineers and operators with expertise in converter dynamics and grid interactions.

A National Testing Facility

This need for testing infrastructure highlights the opportunity to develop a National Electrification Centre. It is imperative that the nation can test and verify operation of a wide range of electrification technologies at the scale at which they will be used in the network. This is particularly pertinent to the power system security pathways identified in this white paper.

The Centre would be a fundamental pillar in the nation's decarbonisation journey enabling design, simulation evaluation and verification of electrification technologies - such as solid-state transformers, energy storage systems, and grid-forming inverters – improving confidence in maintaining grid stability and fostering an innovative electrification sector.

There are inherent risks and complexities associated with all testing approaches, including interoperability challenges, model uncertainty and accuracy, and evolving technology standards. However, a coordinated and adaptive validation framework, supported by the industry, offers an effective pathway to de-risk innovation, enhance reliability, and build confidence in Australia's future grids as part of a national approach to electrification.

Testing, Validation & Risk Mitigation: investigation pathways

1. Determine and establish a multi-level testing capability that allows for independent validation of emerging technologies, enables flexible and accelerated connection assessments, and creates the underlying infrastructure necessary for the development of advanced testing facilities.

07

Regulatory, Market & Institutional Issues

The interaction of technical and regulatory factors in Australia's transforming electricity system is highly consequential.

While materially significant resources could (and some would say should) be devoted to research into how to improve market models and regulatory frameworks from an economic and customer outcome standpoint, this section of the paper is focused on the areas where regulation and market rules have the greatest intersection with the technical aspects of energy system transformation.

Policy time lag to a system in transition

Australia's National Electricity Market (NEM) rapid move to inverter-based resources, creates new system security needs[13] (frequency, inertia, system strength, voltage control) that are not fully captured by energy-only pricing or legacy network incentives. Recent reviews and rule changes recognise this shift and propose new market-facing frameworks. However, there is still a gap between policy intent and day-to-day technical performance, particularly on the transmission system.

Regular reviews and regulatory changes

Several market reviews and regulatory measures relating to system security have been undertaken or are underway:

System security needs through the energy transition[14]
In Nov 2025 AEMO lodged a rule change proposal requesting the Australian Energy Market Commission (AEMC) amend the National Electricity Rules' (NER) planning and procurement frameworks for system strength and inertia to support the efficient and timely deployment of resources required to meet system security needs over the energy transition.

Efficient Provision of Inertia rule change[15]
In 2025, the AEMC determined not to implement a real-time market for inertia. The determination was based analysis suggesting that the overall costs of a new market would outweigh the benefits of procuring inertia given supply is expected to exceed minimum requirements.

Regular reviews and regulatory changes (cont.)

NSW Transmission Framework Review[16]
The NSW Transmission Framework/Planning Review was an independent expert review commissioned by the NSW Minister for Energy in early 2025 to assess and reform the state's electricity transmission planning arrangements, which were seen as complex, duplicative, and not sufficiently coordinated across multiple bodies such as Transgrid, EnergyCo, AEMO and AEMO Services. It aimed to propose features of an optimal planning framework that supports the timely, efficient, affordable and reliable delivery of transmission projects needed to meet NSW's clean energy and net-zero targets, while enhancing clarity of roles, coordination of planning, engagement with communities and integration with the broader National Electricity Market. Following extensive stakeholder consultation, the Final Report released in September 2025 set out around 15 recommendations to streamline and strengthen planning arrangements—including clarifying responsibilities, reducing overlap, improving governance and transparency, and speeding up project delivery—and the NSW Government broadly accepted these recommendations, noting implementation will take time.

Improving Security Frameworks for the Energy Transition (ISF)[17] In 2024, the AEMC introduced a new services/enablement framework (with staged commencements through 2025) to support procurement of security services (including inertia arrangements) and set the requirement for AEMO to publish an annual Transition Plan for System Security. This was a pivotal step toward market mechanisms that explicitly value technical attributes.

AER's Service Target Performance Incentive Scheme (STPIS v6, 2025)[18]
In 2024, the latest version of STPIS for TNSPs amends parameters and suspends the Market Impact Component pending development of an alternative, which explicitly opens the door to better incentive design around congestion and market outcomes.

Transmission planning & access reviews
In 2023, the AEMC's Transmission Planning and Investment Review (TPIR)[19] pushed for timelier, efficient delivery of major projects. In parallel, Transmission Access Reform (TAR)[20] has explored a hybrid model: Priority Access plus a voluntary Congestion Relief Market (CRM)—to sharpen locational signals and reduce dispatch inefficiency from congestion (with Ministers ruling out LMP-based settlement for time being).

Post-2025 Market Design (Energy Security Board)[21]
Published in 2021, this document set the direction for essential system services, transmission/access reform and better integration of distributed energy and inverter-based resources. It highlighted the need for market-based procurement of security services and improved locational signals.

System Strength Framework[22]
In 2021, the AEMC made a rule to shift from a "do-no-harm" principle to proactive, forecast-based system-strength provision. This included charging and planning standards that scale with inverter-based resources connection forecasts. This aligns TNSP obligations with growth of inverter-based resources but remains largely cost-based rather than performance-based.

Frequency response reforms[23]
In 2020, mandatory Primary Frequency Response (PFR) (2020) and Very Fast FCAS markets (operational since October 2023) created new price signals for speed and quality of frequency control. This provides some proof that well-designed markets can deliver technical outcomes.

Are incentives aligned to expected outcomes?

While there has been significant progress in the regulation of power system security services, there are still some remaining issues that need to be resolved beyond the existing reviews and measures.

There are unresolved issues related to incentives as they relate to system security services when it comes to future scenario planning to system security services about the lack of "plan B". If there are delays to syncons, this will require extending thermal generation, especially given supply chain constraints. We saw in Transgrid's PACR[24] that they already were looking at potential redispatch (increase in operating hours compared to typical market operation) of coal for system security perspectives. At a high-level, these actions seek to address uncertainty in the roles of power system actors, the risk ascribed to those roles and the regulatory framework that can govern those roles.

This uncovers an overarching **investigation question** for markets and regulation:

- What is the right regulatory framework and market principles for the future system dominated by inverter-based resources?

More specifically, there are unresolved issues related to incentives, and the administration of incentives, as they relate to system security services. The STPIS[25] focuses on outages and availability, but not on voltage excursions, oscillation damping, dynamic ratings utilisation, or system-strength adequacy at the right nodes and times. Congestion costs are not linked to accountable parties in the absence of access pricing reform.

There is an argument for transparent markets with clear performance metrics for some system services (e.g. inertia enablement and advanced voltage control). The proactive system-strength standard is forecast-driven, yet there are limited outcome-based incentives on measured stability / performance after commissioning.

These issues uncover **additional investigation questions** which will need to be resolved to achieve the system and market's higher-level objectives:

- What is the appropriate designation of roles and responsibilities, and risks allocated to those roles, for administering system security services in the power system?
- How can the system address the weak alignment of incentives to ensure system security services are effectively delivered including real-time system quality beyond outages and availability, linking congestion costs with accountable parties, and coupling planning and performance incentives?

If the market and regulations do not provide clear roles, risk allocation and accountability informed by deep technical expertise, there is a significant risk that system security services will not be delivered when and where they are needed.

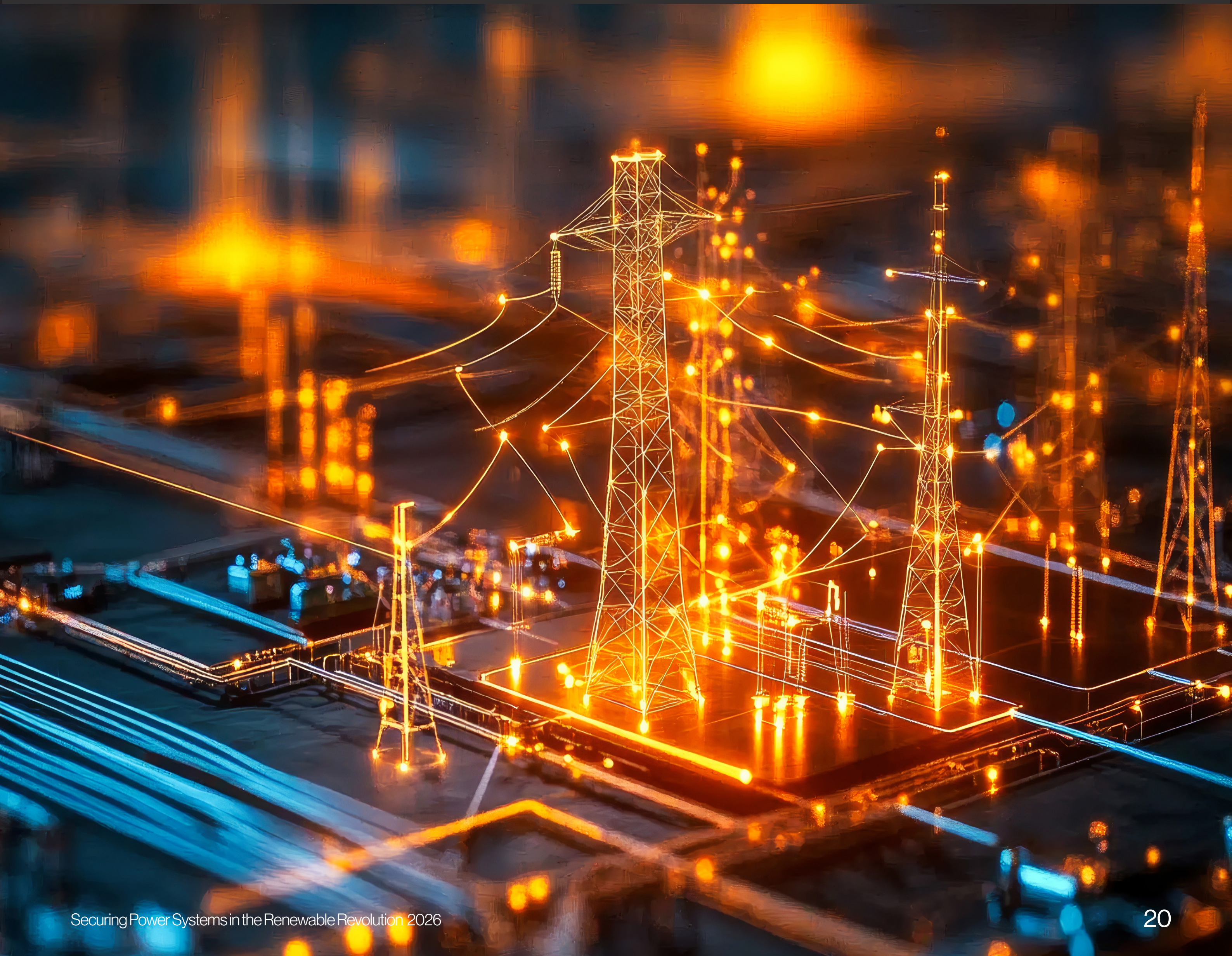
It is recommended that as part of a national approach to electrification, a working group is established to support standards development and the evolution of regulatory frameworks.

Regulatory, Market & Institutional: investigation pathways

1. What is the right regulatory framework and market principles for the future system dominated by inverter-based resources?

2. What is the appropriate designation of roles and responsibilities, and risks allocated to those roles, for administering system security services in the power system?

3. How can the system address the weak alignment of incentives to ensure system security services are effectively delivered including real-time system quality beyond outages and availability, linking congestion costs with accountable parties, and coupling planning and performance incentives?



08

Recommended Actions

> **“…unlike traditional synchronous solutions, GFM inverters can independently create their own three phase voltage vector with a balanced sinusoidal waveform, offering more flexibility in responding to grid disturbances.**
>
> SMA, **June 2024**

8.1 Imminent Challenges to Power System Security

The transformation of our power system from synchronous fossil-fuel based generation to inverter-based renewable resources has profound implications for system security. System security is a complex area relating, but not limited to the provision of inertia and system strength. Historically, synchronous generators have, by virtue of their physics, delivered these services. Sourcing these services from inverter-based resources, largely through GFM inverters, raises technical, economic and regulatory questions. These relate to first principles issues, protection mechanisms, dynamic behaviour and system stability, testing and validation, and markets and regulation.

8.2 Our Response to the Challenge

Government, industry and academia share an interest in answering the questions related to the provision of power system security services in a system dominated by power electronics. This white paper seeks to identify the key questions and put forward a pragmatic and staged pathway answering these questions in the context of a recommended national approach to electrification.

8.3 Critical Investigation Questions

To derive the critical questions, a workshop was convened at the University of NSW on “Securing Power Systems in the Renewable Revolution” on 9 September 2025. The workshop sought to identify the gaps in evidence required to accelerate the acceptance and maturity of new pathways to power system security in Australia.

Following extensive engagement with government, industry and academia, the below investigation questions have been prioritised to meet their various needs across:

- Principles & Future Scenarios
- Power System Security & Protection
- Dynamic Behaviour & Stability
- Testing, Validation & Risk Mitigation
- Regulatory, Market & Institutional Issues

8.3 Critical Investigation Questions (cont.)

Principles & Future Scenarios

1. What is the need for synchronous machines now, during the transition and beyond?
2. What mix of synchronous condensers (SynCons), grid-forming (GFM) and grid-following (GFL) inverters is necessary? What are the boundary conditions?
3. If required, can inverter-based resources (IBRs) provide all power system security services to the system?
4. How would a "Pilot" Future State of the Network be designed to provide confidence of "feasibility at scale" to regulatory authorities?
5. What is the appropriate mix of distribution and transmission-based assets to best operationalise security services?
6. How does this mix change with location, asset availability, demand, supply and penetration of generation, load features and network arrangement?

Power System Security & Protection

1. What is the definition of the term "protection quality fault current" into measurable and verifiable attributes?
2. What is the understanding of and how to evaluate IBR responses to credible grid disturbances and the compatibility with network protection settings?
3. How to evaluate the minimum fault current thresholds (magnitude, duration, waveform) required for dependable operation of representative transmission and distribution protection schemes?
4. To what extent can specifications and inverter system design increase or define the system fault current characteristics to ensure dependable power system protection?
5. Can future protection systems rely on different fault-current properties, not just the magnitude (e.g., waveform signature)?
6. What control functions and specifications are required so fault current can be viably and reliably provided by inverter-based resources to deliver sufficient power system protection? To what degree? Are there alternative parameters?

Dynamic Behaviour & Stability

1. What impact do GFM and GFL converters have on system stability (specifically small-signal stability) when co-located with SynCons? What additional impacts are experienced in remote locations? What are the critical parameters for tuning the operation of these co-located systems?
2. How to optimise the allocation and proportioning of GFM inverters, GFL inverters and SynCons according to network conditions? What is the operating tolerance band between them?
3. Can we dynamically allocate the role of GFL and GFM inverters based on the needs of the broader network?
4. How should GFM inverter-based controls be configured over the longer timeframe (beyond the initial sub-transient / transient period)?
5. How should GFM inverter-based controls be configured after reaching the equipment power / current limit?
6. What is the resulting impact on supervising and protection elements, such as protection relays, and wide area protection schemes?
7. How can faster dynamic response be enabled in a way that can guarantee behaviours across all conditions, including rapidly changing conditions that can conflict with performance objectives?
8. How can GFM technology improve on existing responses from synchronous generators?
9. How can GFM control be designed and GFM dynamics be limited or shaped to maintain responsive and robust performance across a wide range of system conditions?
10. How could new methods be enabled for:
    - impedance scanning and impedance bands for plants under different operating conditions,
    - data-driven stability analysis, and
    - control hardware-in-the-loop testing for wide-area and rapid testing
    - development of open-source models to facilitate the connection process
11. Subject to commercial requirements, how could open-sourced or white-boxed models support the connection process?

Testing, Validation & Risk Mitigation

1. Determine and establish a multi-level testing capability that allows for independent validation of emerging technologies, enables flexible and accelerated connection assessments, and creates the underlying infrastructure necessary for the development of advanced testing facilities.

Regulatory, Market & Institutional Issues

1. What is the right regulatory framework and market principles for the future system dominated by inverter-based resources?
2. What is the appropriate designation of roles and responsibilities, and risks allocated to those roles, for administering system security services in the power system?
3. How can the system address the weak alignment of incentives to ensure system security services are effectively delivered including real-time system quality beyond outages and availability, linking congestion costs with accountable parties, and coupling planning and performance incentives?

8.4 An Action-Oriented Agenda

To achieve technically and economically efficient and effective outcomes for the transformation of Australia's power system, it will be crucial to find answers for these non-trivial questions. By articulating the questions and a recommended set of actions, this paper intends to inform future work to achieve economically and technically efficient alternatives to achieving power system security in the Australian context.

Given the work ahead is both ambitious and trans-disciplinary, the authors assert: *to achieve timely success, the investigative and reform work need to be delivered under an effective framework of industry, government and academic partnership.*

Hence the need for a national approach to electrification. This approach will enable the coordinated and integrated design and execution of workstreams across technical, policy, regulatory and economic dimensions.

8.4 An Action-Oriented Agenda (cont.)

Addressing the questions in a coordinated, integrated way that is facilitated by partnerships between industry, academia and government agencies is the keystone to success.

Thus, the white paper makes the following recommendations:

1. Establish a national approach to electrification to facilitate the investment in activities that will accelerate the adoption and integration of new technologies. This includes advanced inverter controls to deliver power system security measures that are robust and fit for purpose, supporting least-cost outcomes for energy consumers.

2. Undertake an immediate and detailed investigation into the behaviour of inverter-based resources and protection relay performance during grid disturbances. This will resolve uncertainty related to how protection systems respond with high penetrations of wind and solar generation alongside battery energy storage systems.

3. Deliver a wide area network digital twin of critical parts of the National Electricity Market that can simulate future scenarios to identify and resolve integration and control issues that could impact power system security. This will help avoid loss of supply (blackouts) and de-risk the evolution of the grid.

4. Establish a representative working group of deep expertise to inform policy, regulation and standards that can respond to rapid technology developments.

8.5 Conclusion

Partnerships across industry, government and academia are required to develop and deploy the best solutions. Guided by this paper, the authors look forward to collaborating with industry and government agencies through a national approach to electrification to help achieve a decarbonised energy system that is cost-effective, safe and secure for all Australians.

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	Position on approaches to power system security
Australian Energy Market Commission (AEMC)	The AEMO protection grade fault implemented a rule change to reflect the changing need for discrete inertia services to be delivered to the NEM.[26] The rule change was initiated because the AEMC determined that: “The existing framework does not include procurement arrangements for the inertia levels required during interconnected operation to manage system rate of change of frequency (RoCoF) and transient stability. This has the potential to result in an unbalanced procurement which would mean some regions of the NEM under-invest while others bear a disproportionate burden of the investment and so cost. To address this, the final rule introduces a mainland inertia floor (the ‘system-wide inertia level’) for interconnected operation to promote distributed inertia procurement across the NEM. The rule aligns inertia and system strength procurement timelines, allows TNSPs (Transmission Network Service Providers) to procure synthetic inertia to meet minimum inertia levels, and allows inertia and system strength to be procured through NSCAS to address near-term gaps.” The changes aligning the Inertia and System Strength procurement timeframes commence on 1 December 2024. Therefore, the binding procurement obligations for the revised levels (the floor and modified islanding arrangements) commence on 1 December 2027. Under the “efficient management of system strength” rule change, from 2 December 2025 TNSPs as System Strength Service Provider (SSSP) must meet a system strength standard (NER S5.1a.9) comprising: 1. Minimum fault level requirements, for the safe and secure operation of the power system; and 2. Efficient level of system strength, to facilitate the stable voltage waveform of new Inverter-Based Resources (asynchronous generating units and inverter-based loads) surrounding specified system strength nodes. NB: In October 2025, the AEMC determined not to implement a rule change, submitted by the Australian Energy Council, to establish a new real-time market for inertia.

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	Position on approaches to power system security
Australian Energy Market Operator (AEMO)	AEMO is coordinating policy and procedural changes to address the changing nature of generation and the need to provision inertia through explicit planning and services. AEMO has determined that minimum fault level requirements “must be delivered by devices that can provide protection-quality levels of fault current – such as new synchronous condensers, service contracts with existing hydro or thermal units, or through the retrofit of those existing units themselves”.[27] AEMO is commissioning a GFM Inverter Protection-Quality Fault Current Trial, commencing July 2026, to explore new sources of fault current, concurrent with synchronous sources.[28] AEMO is driving the Improving Security Frameworks for the Energy Transition program.[29] Under the rule change, AEMO has been given a new power to enable system security services provided or procured by TNSPs or procured by AEMO to meet minimum system security requirements and to meet stable voltage waveform requirements. One of its measures is the High-Level Implementation Assessment to assess the implementation of its obligations under the rule change, and the associated new scheduler. In relation to new technologies, AEMO suggests that advanced inverters could provide capabilities to support the secure operation of a synchronous power system like the NEM. However, AEMO also states that: “grid-forming (GFM) inverters have been shown in pilot trials and desktop studies to provide capabilities to support system security. It is yet to be shown in practice whether they will be able to replace the capabilities delivered by synchronous machines entirely.” GFM inverters are yet to be contracted to provide any of the four power system security services[30] at scale. Thus, further demonstration of GFM inverters is critical if this technology is to replace the capabilities of synchronous machines. AEMO has laid out future steps that they believe need to be taken to further research GFM inverter capabilities:[31] • Investigate synthetic inertial response • Knowledge sharing of the performance of GFM Battery Energy Storage Systems (BESS) • Develop synthetic inertia specification • Develop access standard for GFM inverters • Update service procurement to consider GFM inverters • Regulatory reform to consider GFM inverters during connection & commissioning

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	Position on approaches to power system security
Energy Corporation of New South Wales (EnergyCo)	To ensure NSW EnergyCo secures network reliability through market modelling by the Consumer Trustee (AusEnergy Services Ltd). EnergyCo considers reliability to be covered by the following Guiding Principles:[32] • Reduce the risks of shortfalls of system strength and other system services • Ensure system reliability and security and thus reduce unserved energy risk For the most advanced Renewable Energy Zone (REZ), Central-West Orana REZ, EnergyCo has directed that system strength be centrally provided by the TNSP, ACEREZ, to "support the stable operation of up to 5.84 GW of initial renewable generation and hybrid generation and storage projects."[33] As a result of the centralised system strength services, access right holders (other than standalone storage projects) will not be exposed to the NER system strength mitigation requirements as part of the connection process. Transgrid considers its system strength obligations in relation to those (REZ-based) generators are limited to meeting NER minimum requirements at declared System Strength nodes. EnergyCo is currently seeking (amongst other things) input into proposed system strength approaches for the New England REZ, specifically seeking feedback on a "proposed approach that would minimise the need for the central provision of capital assets (e.g. synchronous condensers) to meet generator system strength demand."[34][35]
ACEREZ	ACEREZ have highlighted the current connection process has narrowed the focus of controlling plant to meeting the NER performance criteria at a point of connection. ACEREZ has stated that, "A significant volume of time-based simulations are required. However, the control engineering practices for tuning plant to be stable for a wide range of operating conditions involves first establishing the steady state stability through small signal analysis and then testing that stability for large signal stability. In the past the control systems and plant characteristics were analysed using frequency domain mathematics and control feedback methods that provide insight as to speed of response and damping for complex non-linear systems. To solve for the future, we must draw on the lessons of the past which is why in the CWO REZ we are using frequency domain methods applicable to IBR to establish the stability of (wind, solar and battery) generators before commencing time domain simulation. To rely solely on time simulation is solving for an infinite problem."[36] Lessons of this approach could help reduce the complexity and timeframes of the connection process and improve understanding of how power system security services can be provided by both GFM inverters and synchronous condensers.

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	Position on approaches to power system security
Transgrid	Transgrid has published its Project Assessment Conclusions Report (PACR) on meeting system strength requirements in NSW which puts forward a portfolio of solutions to maintain System Security. Transgrid's "preferred portfolio utilises innovative GFM BESS to provide almost half of NSW's System Strength requirements, with Synchronous Condensers providing the other half."[37] The PACR identifies a preferred portfolio of system strength solutions, including:[38] • Ten synchronous condensers on Transgrid's backbone • Five gigawatts of GFM BESS, providing the equivalent strength to another 17 synchronous condensers • Modifications to 650 MW of synchronous generators to enable Synchronous condenser-mode. • Operation of synchronous generators to fill gaps in system strength where required; and • Additional targeted solutions to support new renewables within the New England and Hunter-Central Coast REZs. Transgrid states that, "comprehensive power system and protection studies need to be undertaken to confirm the effectiveness of GFM battery technology to provide minimum fault level support (including for the safe operation of protection devices)" Transgrid, through advice from Aurecon, highlights two key areas where further work and assurance is required for GFM inverters to support minimum fault level requirements:[39] • The ability for GFM BESS to provide a satisfactory fault current response to enable the safe (and successful) operation of protection equipment in the transmission network. • The performance and stability of GFM BESS at their rated current limits, when fault current injection is critical, is not yet established, nor has the stability of these BESS been confirmed for strong areas of the grid. Transgrid "will monitor the evolution and progress of GFM BESS, recognising the potential of the technology for system strength. In the event sufficient progress is made to demonstrate capacity to contribute to the minimum level at scale, this will be considered a material change in circumstance trigger" which under market rules enable a review of investment options. This is consistent with other TNSPs – including Powerlink in Queensland, ElectraNet in South Australia and AEMO Victoria Planning.[40]

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	**Position on approaches to power system security**
Tesla	Tesla supports the adoption of Grid-Forming assets (inverters and batteries) as an evolution in the provision of Power System Security services with a reported 4.5GW / 12GWHrs deployed and under construction across Australia.[41] Tesla states “Grid-Forming Inverters provide voltage regulation, frequency regulation and fault ride through capabilities under extreme grid conditions including when the grid is weak and less stable.”[42] As with SMA, Tesla highlight Grid-Forming assets have “the advantage that response is configurable to the context:”[43] “The modelled rotating component in Tesla’s batteries can respond on a sub-cycle basis– responding to phase angle changes (within 10ms) rather than root-means-squared (RMS) values (within 150ms)– mimicking the electromagnetics of a synchronous generator, but with the additional benefit of flexibility and configurability of the response. Similarly, the System Strength support (such as voltage waveform stability) can be configured and tuned to support the specific grid connection and regional context.” On Fault Current, Tesla note that Synchronous Condensers have a 3-5 p.u overload capability vs typically 1.2 p.u for Grid-Forming Inverters, they note “however if there is a market or actual need for such characteristics” inverters can be reconfigured on battery facilities to “increase the fault current as required”. “Today, the main application for fault current is to distinguish between a fault and normal operation in protection relays. Almost all transmission networks already use differential relays for primary and distance for backup rather than legacy overcurrent relays for their protection schemes (Powerlink Protection Design V11Dec 2024). For the distribution network that still uses overcurrent protection relays, a deep fault in distribution is a shallow fault in transmission – therefore there is not a significant overload contribution required. Furthermore, as we see an increase in generators, the base MVa will increase with more plants contributing to fault current, reducing the need for significant overcurrent capability (at any one asset). ”[44]

Appendix A

Stakeholder views on approaches to power system security.

Stakeholder	Position on approaches to power system security
SMA	SMA states that: "unlike traditional synchronous solutions, GFM inverters can independently create their own three phase voltage vector with a balanced sinusoidal waveform, offering more flexibility in responding to grid disturbances" and GFM inverters are "multi-purpose assets capable of providing inertia, short circuit current, congestion management and other energy services"[45]
Australian Energy Council / Clean Energy Council	AEC & CEC have tabled a joint request to AEMC for an Electricity regulations rule change to enhance strength, inertia and NSCAS market frameworks in the current system.[46] In particular, they are proposing the Transition Plan for System Security (TPSS) be expanded to include specific actionable plans, e.g. AEMO should identify new ways for Essential System Services (ESS) may be provided while traditional providers of essential system services exit the market.

Appendix B

Definitions

Credible Contingency Event

An event on the power system which AEMO expects would be likely to involve the failure or removal from operational service of plant, or a sudden and unplanned change to the level of output, consumption or power flow of plant.[47]

Power System Reliability

A reliable power system has enough generation, demand response and network capacity to supply customers with the energy that they demand with a very high degree of confidence[48]. The purpose of maintaining a reliable operating state is to ensure no customer supply is lost following a credible contingency event, such as the trip of a generator or line. The reliability standard[49] requires at least 99.998% of forecast customer demand to be met each year. To be reliable, the power system must be in a secure operating state.[50]

Power System Security

A secure power system is one that is operated safely within defined technical limits, with ability to withstand credible disturbances, return to secure operation, and restart following a widespread outage. The purpose of maintaining a secure operating state is to prevent cascading failures following a credible contingency event. Security depends on a broad set of technical requirements, including system strength, frequency and inertia, voltage control, transient and oscillatory stability, operability, and system restoration.[51]

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