Amplitude CONSULTANTS a DNV company

Australian Research in Power System Transformation

Topic 6-1: System Services

2024/25 Protection Challenges in IBR Rich Networks – Interim Report

Commonwealth Scientific and Industrial Research Organisation

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Contents

1. Introduction

Australia's electricity system is undergoing a fundamental transformation as synchronous generation progressively retires and inverter-based resources (IBRs) become the dominant source of supply. This transition fundamentally alters the electrical characteristics upon which protection systems have relied for decades. Protection is one of the foundations of a safe and reliable electricity system. When the network experiences a fault, the protection system must detect and isolate the faulty feeder without unnecessary trips of healthy feeders.

As the generation mix shifts toward IBRs, the electrical characteristics of the grid are changing in ways that directly affect how protection behaves. The system is moving from one with strong fault levels, predictable synchronous machine responses, and well understood waveforms into an environment where fault currents are lower, shorter, more controlled, and shaped by inverter algorithms rather than electromagnetic physics. Relays that once operated reliably in previous conditions now operate closer to their limits. Protection coordination that worked for decades is being challenged, and operators are seeing conditions that fall outside their traditional experience.

This project, undertaken by Amplitude in collaboration with CSIRO under Topic 6 of the AR-PST Stage 5 program, addresses these challenges through structured research across eight interrelated activity areas. The aim is not simply to identify challenges already recognised in the industry, but to focus on the solution space: what technologies, strategies, innovations, and practical methods currently exist to help maintain secure, dependable, and resilient protection performance in an IBR-rich grid. The project leverages expertise from a wide range of industry specialists, gathering their insights and perspectives on network evolution in Australia and internationally, and how protection is adapting in practice.

2. Research completed

The project is structured into eight activity areas, each addressing a different dimension of protection performance in the IBR space. Each activity task follows a common methodology commencing with a targeted literature review to understand the current state of knowledge and identify potential solutions and gaps. Findings from the literature inform the development of survey questionnaires used to engage industry specialists to capture professional insights and practical experience. Responses are then synthesised into reports that highlight solutions, lessons learned, and gaps requiring further research.

Task 1 – Interviews with Network Service Providers: Engagement with network service providers (NSPs) focuses on understanding practical field challenges, current mitigation strategies, and solutions deployed in Australian networks. NSPs offer first-hand experience on protection systems in real networks, revealing operational challenges, effective mitigation strategies, and lessons that models or standards may overlook. Discussions with network service providers indicate a clear preference for current differential schemes as the primary transmission-level protection method. However, in networks with high IBR penetration, fault currents can be comparable to load currents, making it difficult for relays to distinguish between genuine faults and normal high-load conditions.

Task 2 – Virtual Power Plants and Future Trends: This task engages VPP operators, DER aggregators, and standards experts to analyse the current role and trajectory of VPPs, including integration of EVs, distributed batteries, communication protocols, and standards like AS/NZS 4777. The focus is on solutions that enhance system strength and support reliable protection. Input from VPP operators and standards experts highlights how these technologies influence system strength and grid flexibility, uncovering current and emerging practices and helping align recommendations with evolving Australian standards.

Task 3 – New Technologies: This task engages OEMs of devices such as small-scale STATCOMs, pole mounted batteries, and Active Filters, assessing emerging solutions, deployment challenges, and their suitability for integration into the network. These OEMs offer critical perspectives on emerging technologies, clarifying deployment considerations, integration challenges, and opportunities to enhance protection performance and network reliability.

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Task 4 – Advanced Protection Strategies: Engagement with protection relay OEMs such as SEL, Schneider Electric, Hitachi, and Siemens, along with protection specialists, reviews advanced protection schemes beyond traditional methods. Discussions with protection OEMs indicate that travelling-wave technology offers a promising solution. Travelling-wave relays detect faults by capturing initial waves that propagate along the line immediately after a fault occurs. These waves arrive within microseconds, well before conventional fault current rises. Travelling-wave relays can determine both the presence and direction of the fault, often operating within a quarter-cycle. This approach makes them largely independent of fault current magnitude and therefore highly effective in IBR-dominated systems.

Task 5 – Academic Research: Engagement with Australian universities focuses on reviewing current and future research trends, exploring collaboration opportunities, and identifying insights that help inform practical solutions. Collaboration with universities provides access to emerging research, novel protection approaches, and experimental methods, ensuring the work incorporates the latest thinking and identifies opportunities for academic-industry collaboration.

Task 6 – Innovative Global Projects: This task reviews international research from organisations such as NREL, IEEE, IEC, and CIGRE to understand global developments in protection systems and identify approaches that could be adapted for the Australian environment. Reviewing international initiatives highlights best practices and emerging trends from around the world, helping adapt proven approaches locally.

Task 7 – Remote Systems and Microgrids: Investigation of protection challenges in isolated power systems, particularly remote mine sites and microgrids, focuses on understanding reliable operation and safety in high renewable penetration scenarios. A principal protection engineer in one of our interviews recounted experiences supporting several mining operations with remote microgrids, ranging in size from 2 MVA to 45 MVA. Total installed renewable generation at these sites was advised as 60–70% of total installed capacity but typically supplied only 10–20% of actual generation. The specialist highlighted advantages of differential protection schemes in microgrid networks with variable fault levels. Nonetheless, approximately 95% of protection systems still rely on traditional time-graded schemes, with best outcomes achieved using communication-based and multiple setting groups.

Task 8 – S5.2.5.10 Compliance: This task assesses protection requirements for voltage, active power, and reactive power instability detection to support compliance with NER clause S5.2.5.10. It investigates potential impact of higher IBR penetration on system stability and sub-synchronous oscillations. Consultation with AEMO and AEMC ensures work meets regulatory requirements, identifying gaps in current protection strategies and guiding practical recommendations for secure, reliable operation with high IBR penetration. Interviews with OEMs indicate the development of new devices that provide one additional control loop to dampen oscillations.

3. Outstanding activities

The approach moving forward ensures the work remains grounded in real-world operational experience while evolving iteratively as industry feedback and new information becomes available. This methodology allows systematic review of findings, resolution of knowledge gaps, identification of practical solutions, and prioritisation of recommendations that will have the greatest impact to stakeholders.

The immediate priority is to finalise the survey questionnaire process, including the addition of high-value contacts where appropriate, and to follow up on survey commitments while continuing structured interviews with stakeholders across NSPs, VPP operators, OEMs, and protection specialists. Presently the project is still in the process of finalising these stakeholder engagements, gathering information to inform the work as it progresses.

As this feedback is received, it will be integrated with the literature review findings, resolving conflicting viewpoints, highlighting knowledge gaps, and identifying actionable solutions. This process allows prioritisation of technologies, processes and approaches that are feasible and implementable in the field, supporting meaningful, practical recommendations.

In parallel, engagement with Australian universities will be completed to access emerging research, novel protection approaches, and experimental methods. This work ensures recommendations incorporate the latest thinking and identifies opportunities for academic-industry collaboration. A comprehensive review of international research from NREL, IEEE, IEC, and CIGRE will benchmark Australian networks against global developments and identify adaptable approaches from overseas experience.

All findings will ultimately be consolidated into a clear, actionable report ensuring recommendations are evidence-based, traceable, focused, and deliver maximum value to stakeholders.

4. Progress Against the Roadmap

This project sits firmly within Stage 5 of the AR-PST roadmap, focusing on understanding and enabling the secure operation of IBR power systems. Protection is one of the key enablers of system security and is central to ensuring the system operates reliably under low-inertia and low-fault-level conditions. With the investigation of the behaviour of protection systems in IBR-rich networks, the project directly contributes to an array of Stage 5 objectives: understanding system operability, identifying where existing protection may be insufficient, and evaluating potential solutions and innovations.

Progress across the eight activity areas is approximately 50% complete. Literature reviews have been substantially completed across all task areas, establishing the current state of knowledge and identifying potential solutions and gaps. Initial stakeholder engagements with NSPs, VPP operators, OEMs, and protection specialists are laying a foundation of practical insight into how protection systems are responding as IBR levels rise. While these consultations are still progressing, they are already highlighting the key challenges emerging in the field.

Early observations are identifying patterns in preferred protection schemes at different renewable penetration levels. The project is gaining awareness of advanced relay elements, tools, and control capabilities that may support improved protection in IBR-rich networks. Impedance measurement relays that previously did not function reliably with IBRs now utilise rate-of-change of impedance elements for improved performance. Newly developed protection algorithms that detect low-inertia power swings, applicable to IBRs, are also now commercially available. At the inverter level, new technology provides an additional layer of control above inverter groups, dynamically adjusting inverter control settings to tune out sub-synchronous oscillations and other undesirable responses.

The work also identifies gaps for future research. Stage 5 does not end with describing challenges, it aims to prioritise areas that require further technical development or standards evolution. The findings are intended to inform both operational guidance for network operators and policy-level considerations.

5. Research relevance to Australia

The value of this work lies in its contribution to understanding and proposing solutions to the challenges posed by high-IBR networks. As traditional protection schemes become less effective in low-inertia systems, there is a need for informed guidance to help operators, regulators, and other stakeholders navigate emerging risks. The AEMO 2024 Integrated System Plan forecasts up to 90% of NEM coal-fired stations potentially retiring before 2035, accelerating the transition to IBR-dominated networks.

Australia leads the world in per-capita rooftop solar installation, with over 2.5 million installations representing more than 10 GW of distributed generation capacity. This study aims to provide practical insights that support decision-making and planning as synchronous generation retires, and to explore how DERs, VPPs, batteries, and other emerging technologies can be better integrated to support network stability. These insights are intended to inform national strategies, including Renewable Energy Zones and the development of secure operating envelopes.

The research focuses on protection in high-IBR networks, examining challenges in regions with low system strength, high solar IBR penetration, and isolated microgrids, conditions that stress traditional protection assumptions and demand careful analysis to maintain reliable operation. Lessons from remote and islanded systems, which often experience high levels of inverter-based generation before the main grid, provide early indications of challenges that may emerge as synchronous generation declines. The growing penetration of distributed energy resources at the distribution network level creates additional challenges requiring focused attention on distribution-level protection coordination, voltage management, and localised system strength per the **AEMO Integrated System Plan**.

All findings are considered within the regulatory context, ensuring alignment with NER S5.2.5.10 and other operational standards, so recommendations are technically sound, implementable, and compliant. The work encourages opportunities for collaboration across industry and academia, enabling universities and research partners to actively contribute and help shape the development of solutions. This work aims to build understanding, foster collaboration, and provide practical, actionable guidance to support the evolution of a secure and resilient high-renewables electricity system.

6. Early Insights

6.1 Microgrids:

Discussions with protection specialists working in microgrid environments within Australia's gold mining sector highlight the increasing relevance of differential protection schemes, which exhibit strong immunity to IBR-driven fault level variability. Despite this, approximately 95% of protection systems continue to rely on traditional time-graded overcurrent schemes, with the best performance achieved through communication-based setting groups that help maintain selectivity amid large swings in fault levels between islanded and grid-connected operation.

A key limitation is the heterogeneous relay fleet typically found on these sites: mixed-vendor devices with differing communication capabilities—alongside legacy digital relays offering no communications at all—restrict the ability to implement full coverage of advanced schemes. As a result, the prevailing strategy tends to prioritise reliability over security. Because HV faults are very infrequent in these networks, some degree of mal-grading is tolerated to ensure dependable operation. A consistent recommendation is to ensure relay fleets are progressively modernised so they can support common, interoperable communication protocols.

Further discussions indicate that weak or unreliable grid connections drive many remote mining microgrids to operate predominantly in islanded mode to maintain production stability. While synchronous condensers have been considered for system strength and fault level support, they are generally regarded as cost-prohibitive. Instead, operators are increasingly favouring lower-cost battery banks, which not only assist with system strength but also provide operational flexibility and support broader energy management objectives.

6.2 New Technologies

OEM discussions revealed a new SEL product technology called powerMAX. The innovation is an integrated microgrid control and power-management system, combining relays, controllers, communications, automation, and logic to manage, protect, and stabilise power systems that include distributed energy resources (DERs), energy storage, conventional generation, and loads. The technology is intended to work not just in standalone microgrids, but also in grid-connected systems, and even for large-scale/utility-level integration.

In systems with high penetrations of inverter-based resources (IBRs), the technology provides a higher-level layer of system coordination beyond individual inverters or inverter groups. It enables rapid islanding detection, adaptive load shedding, generation/load balancing, and real-time control that responds to changing conditions — all with relay-speed performance. Critically, it can dampen sub-synchronous oscillations and suppress undesirable inverter responses, helping maintain system stability even when DERs, storage units, or conventional generation are dynamically dispatched and fault-current characteristics are altered by IBR behaviour.

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In essence, it serves as a supervisory control layer that manages the mix of IBRs, storage, and conventional sources under both grid-connected and islanded modes — enabling seamless transitions, maintaining power quality, protecting critical loads, and improving overall system resilience.

Network-wide deployment of powerMAX is technically feasible and offers significant benefits for stability, protection, and control in IBR-rich systems. While the technology has been successfully deployed in microgrid and utility applications, ongoing work and practical experience continue to inform large-scale dynamic performance, interoperability with diverse assets, standardised commissioning practices, and optimisation of cost-effective integration into existing grid infrastructure. These areas present opportunities to refine and extend supervisory control strategies for modern inverter-dominated networks.

6.3 Advanced Protection Strategies

Travelling wave (TW) elements provide a step-change improvement over conventional distance and differential protection, both of which rely on stable voltage and current phasors—quantities that become less reliable in IBR-dominated networks where fault currents may be limited, highly controlled, or comparable to load current. By acting on the initial high-frequency transients rather than on steady-state quantities, TW algorithms deliver much faster fault detection and more accurate location, improving security and dependability where traditional impedance or current-differential schemes may struggle. This approach is largely independent of fault-current magnitude and insensitive to the reduced sequence components and short-circuit levels and produced by converters.

Discussions with SEL highlight the application of both double-ended and single-ended TW algorithms: double-ended methods use time-synchronised arrival times at both ends for sub-tower-span accuracy, while single-ended methods (and built-in impedance-based backups) provide resilience when communications or timing are limited. TW elements also deliver ultra-fast directional decision and location information that can be used to adapt autoreclose logic and speed restoration.

Although traveling-wave protection is already a proven technology and commercially available through multiple OEMs, including successful deployments on long overhead transmission lines, its wider application in IBR-rich networks presents valuable opportunities for continued advancement. SEL highlights practical considerations—such as the need for high-bandwidth sampling, precise GPS synchronisation, and reliable communications—which are readily met on transmission systems but can be more challenging on shorter, cable-heavy, or noisier circuits.

Ongoing work to enhance noise immunity, streamline commissioning, and standardise testing for sub-transmission and distribution contexts will broaden the range of conditions in which TW protection can operate effectively. Since the technology is well-established, remaining research represents an opportunity to expand its applicability rather than a limitation of its core principles.

7. Work moving into 2026

Based on preliminary findings and identified gaps, the following research priorities are recommended for 2026/27:

7.1 Distribution Network Protection

Address protection challenges at the distribution level as DER penetration increases. Traditional fuse-based protection faces significant challenges under low fault-current conditions from high IBR penetration. Research should focus on coordination between DER protection and network protection systems, addressing voltage management and localised system strength issues identified in the AEMO Integrated System Plan.

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7.2 Grid-Forming Inverter Protection Integration

Gain stakeholder insights into how grid-forming inverter capabilities affect protection system design and coordination. As grid-forming solutions, advanced relays, STATCOMs, active filters, and virtual power plants emerge as technologies to enhance system strength and protection performance, research should focus on their interaction with existing protection schemes, operational safety (i.e. residential CER grid forming while grid connected) and optimal integration approaches.

Grid-forming (GFM) inverters represent a promising solution for enhancing stability and resilience in inverter-dominated networks, yet their wide-scale deployment faces several practical challenges. One major roadblock is interoperability with existing assets: GFM inverters must operate alongside synchronous generators, grid-following inverters, and legacy protection schemes, which can lead to unexpected dynamic interactions, oscillations, or miscoordination of protection. In addition, low or tightly controlled fault currents, combined with the fast response of GFM inverters, complicate traditional protection design, requiring adaptive or supervisory strategies that can reliably detect and isolate faults without compromising system security.

Operational and economic considerations further constrain implementation. Coordinating multiple GFM units across wide-area networks demands advanced control strategies, high-speed and cyber-secure communications, and rigorous system monitoring — all of which increase both capital and operational costs. Moreover, the lack of fully harmonised standards and commissioning protocols for GFM functionality introduces uncertainty for utilities and grid operators considering network-scale adoption, particularly in grid-connected or weak-grid conditions.

These challenges, however, highlight compelling research opportunities. Investigations into network-wide dynamic performance under diverse contingencies, development of adaptive protection schemes compatible with low-fault-current environments, and optimisation of supervisory control for coordinated inverter operation are all critical. Additional focus on pilot projects, standardised commissioning procedures, and cost-effective integration strategies can help bridge the gap between microgrid-scale deployments and broad utility-scale implementation. Addressing these gaps will not only support more reliable integration of high penetrations of inverter-based resources but also advance the operational and protection frameworks needed for next-generation power systems.

Possible coupling of grid-forming inverters with other emerging technologies such as SEL's powerMAX should be investigated to evaluate coordinated dynamic control strategies ranging from individual microgrids to wider-area network operations, exploring opportunities for enhanced stability, protection performance, and supervisory-level management.

7.3 Impedance-Based Screening Methodologies

Develop standardised frequency-domain methodologies for screening and assessment of sub-synchronous oscillation risks, building on AEMO's Generator Insights Screening Tool (GIST) implementation. Research should address the inadequacy of traditional Short Circuit Ratio (SCR) metrics for predicting Sub-Synchronous Control Interaction (SSCI) risks in high-IBR networks.

7.4 Adaptive and Intelligent Protection Systems

Validate and refine adaptive protection schemes that can respond to changing network conditions. The use of communication-based setting groups to maintain selectivity amid large fault level swings between islanded and grid-connected operation has shown promising results in microgrid applications. Research should extend these approaches to broader network applications and investigate machine learning methodologies for protection system optimisation.

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7.5 Regulatory Framework Evolution

Support the evolution of protection standards and operational practices through evidence-based recommendations. As the work identifies gaps for future research, it should prioritise areas requiring further technical development or standards evolution, helping shape the next phase of research and regulatory development.