Australian Research in Power System Transformation

Topic 1 – Inverter Design

2024/25

Commonwealth Scientific and Industrial Research Organisation

19 December 2025

Contents

1. Introduction

Inverter-based resources (IBRs), including grid-forming (GFM) and grid-following (GFL) inverters, are increasingly relied upon to support system strength, maintain voltage stability, and respond to faults. Their fault behaviour in low-inertia, weak-grid environments differs markedly from synchronous machines. This poses challenges to system stability and protection schemes.

At the same time, inverter-based loads (IBLs) such as data centres, EV chargers, electrolysers, and industrial drives are becoming major contributors to system dynamics. These loads feature complex power electronic interfaces with some similarities but often with more differences with IBRs. Current modelling frameworks lack the modularity and performance integration needed to accurately simulate their response to disturbances and assess their impact on the grid.

Previous work completed by researchers through various stages examined how large signal stability can be improved by appropriate inverter tuning, impact of various control system approaches and its impact on large-signal stability and proposed design and tuning criteria. Complementing the work completed in previous stages, this work focuses on the three emerging needs in the realm of converter control design. They are:

a. Task 1: IBR response during the fault

Unlike synchronous machines, IBRs can flexibly control their interaction with negative-sequence conditions during unbalanced faults. This work investigates how GFL and GFM inverters behave under such conditions. The work aims to identify which control behaviours support faster and more stable voltage recovery, better protection coordination, and future standardisation.

b. Task 2: Technical standards for GFM accounting for impact on protection systems

The GFM inverters behave as voltage sources behind impedance and exhibit nonlinear behaviour during faults and post-fault recovery. This behaviour can impact power system protection schemes. Using detailed modelling, this work will examine the risks of mis-operation of protection schemes and develop technical recommendations.

c. Task 3: Modelling framework for IBLs

The growing diversity of IBLs (e.g. data centres, EV chargers, electrolysers) demands a flexible, scalable modelling structure that can accommodate varying technologies and control schemes. The focus of this work is to develop a modular interface specification and modelling framework for IBLs which is applicable for system studies.

2. Research completed

Previous AR-PST research stages (stage 1 – Monash University), (stage 2 – Monash University, EPRI and The University of Sydney), (Stage 3 – Monash University and EPRI), (Stage 4 – Monash University) focused on improvement of the control system design to support stable operation of IBR during weak grid conditions. The control system designed focused on the improvement of the transient stability margin, development of the tool to assess this margin for GFL and GFM inverters in single and multi-IBR systems. The analysis also focused on enhancing IBR response during and subsequent fault. While the focus of the previous research has been on overall improvement of the power system transient stability, no consideration has been given to IBR response during the fault and its impact of the system protection

Stage 5 provides complementary investigation and focuses on the impact of fault response on power system protection and how various control architecture provides different fault response from the GFL and GFM inverters. To date, following research has been completed for stage 5:

2.1 Task 1: IBR response during response during the fault

Activity 1: Literature review and benchmarking

A detailed technical report has been prepared that investigates how GFL and GFM inverters behave during unbalanced fault conditions focusing on negative sequence current flows, comparing it against normally expected response from protection system point of view, and assessing its impact on the power system and IBR control stability. The report also reviewed existing practices around the world on the topic of negative-sequence current provision from IBRs, provides detailed discussion on various control philosophies to adjust IBR response during the fault and provides tangible practical design targets that could be considered for standardisation. A detailed review of international standards and guidelines has been carried out to collaborate international learnings on requirements from IBR during the fault conditions. An initial practical design targets have been developed for IBR with focus on the requirements for system protection operation.

Activity 2: EMT model development

A number of EMT models including various technologies e.g. Wind Farm, Solar Farm, BESS in GFL and GFM form have been developed. These models include current limits and controlled sequence current injection when required. They have been integrated into a simple system to analyse their response during the fault under various operating conditions

Activity 3: Comparative analysis of GFL vs GFM impact

Through various operating conditions a detailed analysis has been carried out. This analysis focused on the performance of GFL and GFM plants during the fault, it compares their performance against each other as well as a synchronous generator. Focus has been on the magnitude and direction of the negative sequence currents, phasor relationship between various quantities during the fault, fast and stable response and effective negative sequence impedance during the fault. These aspects are critical for adequate protection system operation and therefore they have been focused during the comparison. The analysis carried out using single-machine infinite bus (SMIB) and multi-machine system.

Activity 4: Practical design targets

The investigation of the impact of various control approaches on the performance of GFL and GFM plants has been completed. The outcome has been mapped into the form of ‘practical design targets’. These design targets focus on phasor relationship between various quantities during the fault and management of the composition of positive and negative sequence currents during the disturbance.

3. Outstanding activities

The following activities remain in this stage 5 project:

Task 2: Technical standards for GFM accounting for impact on protection systems

- EMT model development and protection compatibility assessment
- Impact of potential loss of synchronism and auto-reclose events
- Development of technical performance requirements

Task 3: Modelling framework for IBLs

- Technology characterisation and performance mapping
- Interface specification and model structure

4. Progress against the Roadmap

The Roadmap Topic 1 focus on development of capabilities, services, design methodologies and standards for Inverter-Based Resources (IBRs) to ensure power system reliability.

Stage 1 created a research roadmap addressing key questions on IBR control, services, capabilities, and protection, engaging stakeholders like universities, governments, and CSIRO. It outlined five major tasks plus shared tasks with other GPST topics. Stage 2 developed a practical tool to evaluate multi-IBR system stability, introducing indices for quick transient stability margin assessment. Stage 3 focused on grid-forming inverter design and control to enhance reliability in IBR-dominated grids. Stage 4 analysed sensitivity of control parameters and improved large-signal stability tools, offering practical tuning and design guidelines.

Stage 1 to 4 focused on the IBR control design to support stable operation of the power system and improvement of transient stability margin while giving no consideration to either IBL control design or IBR during the fault behaviour and its impact on the system and protection. This gap is being addressed in stage 5.

The Stage 5 work completed and planned aligns well against the Roadmap for Topic 1. Specifically, the following roadmap areas are being investigated through the stage 5 work:

- IBR response during response during the fault: This work focuses on interrelationship between IBR and power system protection system where it examines the impacts of various control approach on power system protection adequacy.
- Technical standards for GFM accounting for impact on protection systems: This task buildings on the learnings from the previous talk to support revision (if needed) of Technical Standards in Australia.
- Modelling framework for IBLs: The aim of this task to develop bespoke models of IBLs and modelling framework for IBRs that support system studies.

5. Research relevance to Australia

Australia is at the forefront of the global energy transition, with a rapid shift toward inverter-based resources (IBRs) such as grid-forming (GFM) and grid-following (GFL) inverters. This transition is reshaping the operational landscape of the National Electricity Market (NEM) and the Western Australia Electricity Market (WEM). This uptake has displaced traditional synchronous generators from the grid and some of the system security supports that these synchronous generators provide. The IBRs are increasingly tasked with supporting system strength, maintaining voltage stability, and providing fit-for-purpose response during the fault. Their behaviour during faults, especially in low-inertia and weak-grid environments, differs significantly from synchronous machines, challenging system stability and adequate protection operation. An inappropriate behaviour during the fault could see a rise in un-faulted phase leading to undesired consequences to the grid. The industry must now grapple with how to ensure reliable protection performance in systems dominated by power electronics.

Recently AEMO has issued a Statement of Need under clause 3.11.12(a) of the National Electricity Rules to acquire Type 2 transitional services for the purpose of conducting a Grid-Forming (GFM) Inverter Protection-Quality Fault Current Trial[1]. The trial aims to demonstrate whether GFM inverters can provide fault current of sufficient magnitude, duration, and composition (e.g. relevant positive and negative sequence components and waveform properties) for protection relays to operate correctly under diverse system operation and fault conditions.

AEMO recently published two reports that highlights investigating IBRs to provide protection quality fault current. Both reports[2][3], highlighted several system incidents that identified that traditional protection systems are not well-suited to the quality of fault current supplied by the IBRs. These reports recommended enhance modelling and simulation practices to study ‘composition’ of the fault current contribution from IBRs.

Currently, a key unresolved issue is whether IBRs can reliably provide minimum system strength, particularly in terms of protection adequacy. Before revising grid-codes to include IBRs as providers of protection-quality fault current, it is essential to understand their capabilities and limitations. The research conducted under Stage 5, Topic 1, is highly relevant to this effort. By simulating the fault response of GFL and GFM inverters and evaluating their ability to provide “protection-quality fault current,” the project addresses a key technical barrier to broader IBR adoption. These simulations are grounded in technologies currently deployed in the NEM and WEM, ensuring that the findings are directly applicable to real-world Australian grid conditions. For Australian industry stakeholders, transmission network service providers (TNSPs), distribution network service providers (DNSPs), inverter manufacturers, and renewable energy developers, this research offers actionable insights. The models being developed to investigate IBR response during the fault are similar to the technologies present in the National

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[1] https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/transition-planning/transitional-services---type-2-services/grid-forming-inverter-protection-quality-fault-current-trial

[2] https://www.aemo.com.au/-/media/files/initiatives/engineering-framework/2025/grid-forming-and-grid-following-inverter-fault-current-contribution.pdf

[3] https://www.aemo.com.au/-/media/files/initiatives/engineering-framework/2025/grid-forming-bess-fault-current-contribution-study-scope.pdf

Electricity Market (NEM) and Western Australia Electricity Market (WEM). Therefore, the leaning outcomes would provide useful information on the interrelationship between IBRs and protection in the context of the NEM and the WEM.

Australia’s electricity system is seeing rapid growth in large, non-traditional, inverter-based loads, with some proposed facilities reaching several hundred megawatts to over one gigawatt. These inverter-based loads can either support or challenge stability depending on their controls and how they interact with the network. At present, fit-for-purpose dynamic models are generally not available. International practice still leans on simplified composite load representations that do not capture key internal controls, protection behaviour, or dynamic interactions, which can mask vulnerabilities such as unexpected tripping, adverse interactions, and oscillatory instability, particularly in low system strength conditions. International incidents involving data centre disturbances reinforce the need to improve modelling. Australia therefore needs a scalable, high-fidelity modelling framework that defines what to represent, at what level of detail, and for which study types, without adding complexity where it is not justified.

Furthermore, excluding any confidential or sensitive data used, the EMT models developed will be released to CSIRO to share with the research community to scrutinise, change, grow, or otherwise use as they see fit. Furthermore, by releasing the EMT models to CSIRO for broader use, the research fosters collaboration and innovation across the national research and engineering community.

6. Recommended research priorities

The following research priorities are recommended for the 2026/27 program.

- Validate model performance under high IBR-penetration or similar conditions to verify accuracy and applicability of research recommendations, through the following two approaches [New research topic]:
    - Protection relay bench testing: Feed high-resolution waveforms from the existing modelling response into physical relay equipment and assess the relay performance.
    - Validation through field measurements: Use high-resolution field measurements from network protection operation as an input to simulation models to assess and verify their accuracy.
- Integration of relevant protection relay models into system studies [Alignment with Major Task 4: Protection and Reliability of Topic 1 (Inverter Design)]:
    - Develop and incorporate transmission protection relays models into real-world system studies (at least for IBR rich areas). Model relevant aspects of operating logic of protective relays, including their dynamic response to varying fault current magnitude, phase angle and impedance, harmonics and any filtering used.
    - Use developed models to identify potential transmission relay mis-operation and suggest remediation measures.
- Dedicated screening methods for IBL [Alignment with Major Task 5: Trending Topics of Topic 1 (Inverter Design) and Topic 2 (Stability Tools and Methods)
    - Develop a screening method, tailored specifically for IBLs, to select the minimum modelling detail needed, rather than borrowing screening approaches used for IBRs.
    - Use the screening outcome to assign PDT versus EMT studies and an appropriate aggregation level.
- IBR and IBL Interaction Studies [Alignment with Major Task 5: Trending Topics of Topic 1 (Inverter Design)]:
    - Explore combined dynamics of IBRs and IBLs under weak-grid conditions.
    - Assess implications for stability and protection coordination.
    - Determine what changes, if any, are needed to commonly used stability assessment methodologies and tools for IBR-only scenarios.